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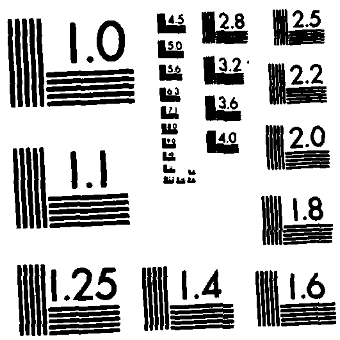

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AN EXPERIMENTAL ANALYSIS
IN MODERN MODAL CONTROL

THESIS

AFIT/GA/AA/82D-11 George F. Studer, Jr.
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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

George F. Studor, Jr.
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A

PREFACE

I would like to thank my advisor, Dr. Calico, for his calm, assuring direction in the midst of seemingly hopeless times. A special thanks to Capt. Clark Briggs for his diligence and understanding in the digital microcomputer software and hardware development so essential to this thesis. My wife, Anita, has been most understanding and has actively supported me by lifting my spirits, by keeping me healthy, and by even typing the thesis. My desire for the student who resumes this research is that he or she will receive the quality of support I have recieved.

George F. Studor Jr.

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ABSTRACT

Experimental demonstration of modern modal control of a flexible clamped-clamped beam in bending was accomplished. Pole placement techniques in conjunction with a Leuenberger Observer were used for controller development. Available microcomputer computational capabilities drove the reduced order model to a two mode representation. The controllers, designed with varying degrees of robustness, demonstrated the limitations of reduced order controllers in even the simplest of systems. Sensor and actuator position are demonstrated to be of paramount importance in the modern controller LQ design.

INTRODUCTION

The space shuttle is operational. The USSR has a permanent presence in space. Private industry is well on its way to having its own satellite launching facility. These recent developments can only mean one thing: trends towards larger, and more complex space structures are quickly becoming a reality. Demands in pointing, jitter, and surface tolerances for these satellites will require more robust and adaptive controllers due to inaccuracies in the mathematical models and changing mass distribution. Designing a controller for these satellites amounts to attempting to control the minimum number of structural modes in order to maintain desired shape and attitude control requirements. Unfortunately, this reduced order controller is affected by the structure's real modes not included in its model. Their effect on control inputs is called control spillover and their effect on sensor outputs is known as observation spillover. Both can cause structural instabilities which exceed the design requirements.

Calico and Janiszewski (Ref 1) demonstrated that elimination of either observation or control spillover will ensure system stability. The number of modes whose observation spillover can be eliminated is one less than the number of sensors, while the number of modes whose control spillover can be eliminated is one less than the number of actuators. It becomes obvious at this point that the most practical implementation will be elimination of observation

spillover because of the physical limitations of implementing a myriad of actuators.

Computer simulation of this phenomena has been demonstrated repeatedly (Ref 1), and controller design for large space structures has progressed rapidly in recent years. These developments are now available for demonstration of control on physical structures. Schaechter (Ref 2) has demonstrated active shape and dynamic control by using various control law design approaches, including adaptive control, and demonstrated various microprocessor control capabilities on a very flexible clamped-free 12.5 foot beam. However, the requirements for sensor and actuator sensitivity, as well as computational capability preclude the use of such a sophisticated set-up to demonstrate active modal control.

The approach used in this experiment closely parallels a control demonstration by Herrick (Ref 3) on a flexible, 5 foot clamped-clamped beam. This simple case is a reasonable starting point for demonstration of active modal control. Even for this simple case, computer hardware available impacts the structure and complexity of the test significantly. The result is a control design based on a significantly reduced order model and an observer based on only a single measurement.

The objectives of this experiment are to: 1) demonstrate active modal control; 2) demonstrate effects of observation spillover of residual modes not modeled in the controller; and 3) provide a basis for further modal control testing at the Air Force Institute of Technology (AFIT).

EXPERIMENTAL APPARATUS

The laboratory developed to demonstrate active modal control consist of the test bed and beam, modal identification equipment, and control implementation equipment.

The test bed is very massive (over one ton) with rigid beam clamps and rigid actuator mounts. The beam is mounted on edge, and the actuators provide force perpendicular to it in the horizontal direction. It was desireable to keep the first mode of vibration above 10 hz since the lightest accelerometer available (2 gm) was only calibrated down to that frequency. The beam chosen therefore was a 61.5" x 1" x .25" beam of 2024-T-4 aluminum, clamped at both ends. The accelerometer is the piezoelectric type with a preamplifier within, and a selectable gain amplifier also provided. The actuator is a typical classroom shaker employing a voice coil system and has a sizeable shaker core mass(341gm). The test bed is versatile in its ability to reconfigure present equipment and can also accommodate mounting of larger and more complex test structures. The details of the equipment set-up are located in Appendix 1.

The equipment used for modal parameter identification consists of the apparatus used for sine dwell identification and the apparatus used for spectrum analysis. Sine dwell equipment includes a digital frequency counter, two root mean square voltmeters, a storage oscilloscope, and a sine function generator. The spectrum analysis utilizes a band limited white noise generat r, a signal correlator, and a spectrum

display. The spectrum display includes storage display of power spectral density and transfer to plotter for hardcopy results.

The sensor and actuator just described were utilized in the system to implement the control algorithm shown in Fig 1.

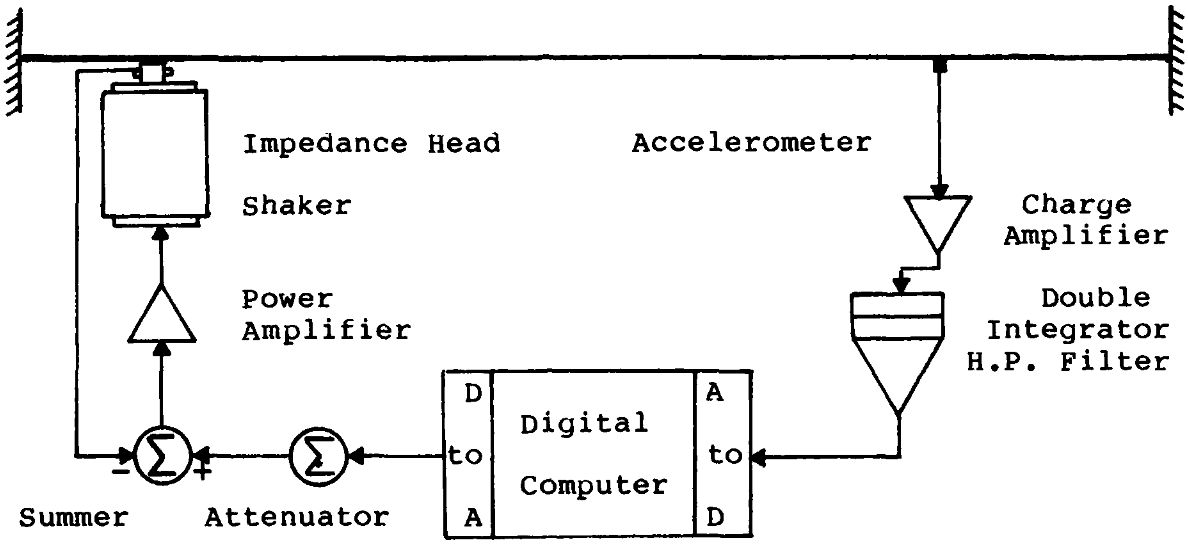


Figure 1. Laboratory Control Components.

The accelerometer is calibrated periodically, including its wires,and the tiny operational amplifier inside also helps guarantee accurate sensitivity and reduced noise. A vibration meter specifically designed for vibration testing incorporates a 5 Hz high pass filter and outputs the desired displacement signal.

The A/D and D/A converters, memory, and single board computer were housed together and access was obtained by a video terminal. Floppy disk program storage was essential to both software development, implementation, and data analysis.

A simple set of potentiometers attenuated the desired

force signal so that a summer could compare it to the force output signal of the impedance head. The pot settings could be very accurately controlled using the analog computer's digital readout in the pot set mode. This became helpful when compensating for the input scale factor in the digital control implementation. In addition, the accelerometer within the impedance head could have provided negative damping to more closely approximate the true beam's dynamics. However, measured beam damping closely matched the light predicted damping in modal identification testing and was therefore not used.

EXPERIMENTAL PROCEDURE

The experimentation consists of modal parameter identification, computer software development, and finally the control experiment.

The beam's modal parameters of concern are natural frequencies and damping. Two methods were used to identify these parameters: swept sine and spectrum analysis.

Swept Sine. Using the set-up decribed in detail in Appendix 1, a single actuator was driven using a constant root mean square voltage. Then the magnitude of the transfer function between the force in and the acceleration out was calculated for a range of frequencies near each natural frequency. The frequency was determined accurately from the digitally displayed signal period. Then the magnitude of the transfer function was plotted versus frequency, and the peaks were used to identify the first four natural frequencies (ω_i) of vibration. The half power method was then applied to determine the damping ratio (ζ_i).

Spectral Analysis. The shaker was driven by a bandlimited white gaussian noise generator which inputs equal power to all frequencies within its bandwidth. Then a number ot samples (on the order of 2exp15) of the accelerometer output were correlated with a controllable period, T, between samples. The spectrum analyzer takes the Fourier Transform of this autocorrelation and displays the accelerometer signal's power spectral density. The sensitivity of the frequency scale, Δf, displayed on the horizontal axis is a function of the sampling

period, T:

$$\Delta f = 1/(20T) \text{ (Hz/cm)} \tag{1}$$

Typical values for, T, are 10ms, 3.33msec, and 1msec which allow frequency ranges of 0-50Hz, 0-150Hz, and 0-500Hz. Care must be taken that the bandwidth of noise input does not excite beam natural frequencies higher than the sampling ability of the correlator. This would manifest itself in the form of false spectral content in the frequencies within the bandwidth of the spectrum analyzer(aliasing).

The natural frequencies and damping were obtained from the plots of power spectral density in a similar manner as with swept sine except that now the PSD of the output is plotted versus frequency where:

$$\text{PSD } y(t) = |H(j\omega)|^2 \times \text{PSD } f(t) \tag{2}$$

In Eq 2, f(t) is the force input signal, y(t) is the accelerometer output signal, and $|H(j\omega)|$ is the magnitude of the transfer function.

Background noise was also examined in this manner to determine the significance of its effect on the system. A coherence and Modal Assurance Criteria analysis was not required because the beam natural frequencies were expected to be widely separated and lightly damped.

Software Development. Computer software was developed to improve the speed of the single board computer (on the S-100 bus) from 2.5 MHz to 5.0 MHz operation. Logic was then implemented in machine code to obtain accurate time

measurement from the computer's 5 MHz system clock. Next, the machine language program for operation of the analog to digital board and the digital to analog board was developed. The boards were calibrated and then checked using simple multipl channel input-output routines. A first attempt at a control algorithm was written in Fortran, but was found to be much to slow to obtain the desired sampling rate of 200 Hz. This rate was chosen to obtain approximately six samples per cycle of the second vibrational mode of the beam.

A number of techniques should be noted here which can quickly reduce the computation time for real time data processing beyond hardware improvements:

1) Use integer arithmetic where it is possible to do so and still obtain the desired accuracy.
2) Avoid inefficient computation logic and divides.
3) Use the assembly language version of the higher order language program to identify ineffective and redundant commands created by the compiler.
4) Avoid the excessive use of subroutine calls, data storage look-ups, and unnecessary 16-bit loads.

After optimization, however, the control algorithm became specific to the number of modes controlled, the number of sensors, the number of actuators, and the scaling factors required to avoid signed 16-bit overflow. Future experimentation will require scheduled events to occur in an intricate manner. A series of programs for control implementation were developed for this purpose and can be found, along with a number of test programs, in the laboratory

as documented in Appendix 8. The control implementation program and its subroutines are contained in Appendix 5.

The Control Experiment. The control was applied and evaluated for two cases: initial condition input and continuous vibration input. The initial condition applied was a step input using a static deflection of the beam center of approximately one third of an inch. A digitized temporal estimate of the first two modal amplitudes was the analysis tool used to compare modal response parameters without control, with only the force loop around the shaker active, and with control applied (for details, see Appendix 1).

The continuous vibration applied was white gaussian noise limited to , 50Hz, 150Hz, and 500Hz at RMS voltage levels of .1, .2, and .3 volts. This was applied through a second shaker positioned at the end opposite to the control shaker and equidistant from the beam center. Incorporating the results of previous analysis by Hungerford (Ref 4), care was taken not to place either actuator near a node of the first four mode shapes to avoid diminished control authority. Also to avoid large actuator deflections which might cause nonlinearities, the actuators were not centrally located. The sensor was also located away from the nodes to avoid a theoretically infinite response time. Controlled modes and observation spillover terms from the third and fourth modes were then examined by spectral analysis for the various cases, and compared to theoretical calculations' expected root migration due to the control applied.

THEORETICAL DEVELOPMENT

The development of the control algorithm, its elements, and its effects on other system components must begin with the test beam. The controller is then designed, and problems involving its implementation are also addressed here. Finally the equipment sensitivities are calibrated and matched.

The Test Beam. Physical properties are identified below:

Material: 2024 T-4 Aluminum

Length: 61.5" = 1 Nondimensiional Length = 1 NL

Actuator Position: $x_a = 4.9170/61.5 = 0.079956$ NL

Sensor Position: $x_s = 48.468/61.5 = 0.788106$ NL

Cross-Section: 1.0" x 0.25"

Density: $\rho = 0.097 \text{ lbm/in}^3$

Modulus of Elasticity: $E = 10.1 \times 10^6 \text{ lbf/in}^2$

Area Moment of Inertia: $I = bh^3/12 = .001302 \text{ in}^4$

Mass per unit length: $m = \rho A/(12g)$

$= 0.097(.25)/32.2(12)$

$= 6.27588 \times 10^{-5} \text{ lbf-sec}^2/\text{in}^2$

Natural Modes. It was first necessary to determine the natural modes and frequencies for a uniform clamped-clamped beam in bending. The general equation of motion for a beam in bending is:

$$\frac{\partial^2}{\partial x^2}\left[EI \frac{\partial^2 v}{\partial x^2} \right] = - m \frac{\partial^2 v}{\partial t^2} \tag{3}$$

where the form of v(x,t) using the assumed modes technique is:

$$v(x,t)=\sum_{i=1}^{n} V_i(x)v_i(t) \tag{4}$$

For a uniform beam the spatial coordinates $v_i(t)$ satisfy:

$$V_i'''' - \omega_i^2(\rho A/EI)V_i = 0 \tag{5}$$

The solution to this homogeneous equation is:

$$V_i(x)= C_1 \sin(\beta_i x) + C_2 \cos(\beta_i x) + C_3 \sinh(\beta_i x) + C_4 \cosh(\beta_i x) \tag{6}$$

$$\text{where } \omega_i^2 = A\beta_i^4/EI \tag{7}$$

Boundary conditions for the clamped-clamped case are:

$$V_i(0) = V_i'(0) = V_i(L) = V_i'(L) = 0 \tag{8}$$

Applying the boundary conditions, we have:

$$V_i(0) = 0 = C_2 + C_4$$

$$V_i'(0)= 0 = C_3 + C_4$$

$$V_i(L) = 0 = C_1 \sin(\beta_i L)+C_2 \cos(\beta_i L)+C_3 \sinh(\beta_i L)+C_4 \cosh(\beta_i L) \tag{9}$$

$$V_i'(L)= 0 = {}_i[C_1 \cos(\beta_i L)-C_2 \sin(\beta_i L)+C_3 \cosh(\beta_i L)+C_4 \sinh(\beta_i L)]$$

Combining these relationships gives:

$$\begin{bmatrix} [\sin(\beta_i L)-\sinh(\beta_i L)] & [\cos(\beta_i L)-\cosh(\beta_i L)] \\ [\cos(\beta_i L)-\cosh(\beta_i L)] & [-\sin(\beta_i L)-\sinh(\beta_i L)] \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

Zeroing the determinant is equivalent to:

$$\cos(\beta_i L)\cosh(\beta_i L) = 1 \quad (11)$$

From Eq (7) we find the solutions to Eq (11) to be:

$$\omega_i = (\beta_i L)^2 [EI/mL^4]^{.5} \quad (12)$$

where

$$(\beta_1 L) = 4.730 \qquad (\beta_2 L) = 7.853$$

$$(\beta_3 L) = 10.996 \qquad (\beta_4 L) = 14.137$$

and for larger values of i:

$$(\beta_i L) = (2i+1)\pi/2$$

Assuming lengths will now be thought of in terms of beam lengths, the theoretical values for the beam's natural frequences are for L = 1 NL:

β_1 =4.73: ω_1 =85.6278 rad/sec or 13.6281 Hz

β_2 =7.853: ω_2 =236.028 rad/sec 37.565 Hz

β_3 =10.996: ω_3 =462.767 rad/sec 73.652 Hz

β_4 =14.1372 ω_4 =764.922 rad/sec 121.740 Hz

Normalizing The Eigenvectors. Common practice is to normalize with respect to the mass. This requires:

$$\int_0^L m\, V_i^2(x) = 1 \qquad i=1,2,3,\ldots n \tag{13}$$

So,

$$V_i(x)=C_1 \sin(\beta_i x)-C_1 \sinh(\beta_i x)+ Z_i C_1 \cos(\beta_i x)- Z_i C_1 \cosh(\beta_i x) \tag{14}$$

where

$$C_2 = Z_i C_1 \tag{15}$$

Solving for C_1 and C_2 from Eq (8) and Eq (13) (in Appendix 2):

$$\begin{aligned} &\text{For } i=1: \quad C_1 = .80452 \quad \text{and} \quad C_2 = -.81885 \\ &\text{For } i=2: \quad C_1 = .81926 \quad \text{and} \quad C_2 = -.81862 \end{aligned} \tag{16}$$

So that

$$V_1(x) = .80452[\sin(4.730x) - \sinh(4.730x)] + .81885[\cosh(4.730x) - \cos(4.730x)] \tag{17}$$

$$V_2(x) = .819261[\sin(7.853x) - \sinh(7.853x)] + .81862[\cosh(7.853x) - \cos(7.853x)] \tag{18}$$

LQG Regulator Development. Under the assumptions of linear models, quadratic cost criterion, and white Gaussian noise inputs, the design of the optimal controller can be completely separated from the design of the estimator. Using

Hungerford's development of the beam model developed by Balas (Ref 6), the optimal control problem can be expressed by the state equations:

$$
\begin{aligned}
\dot{\bar{X}}c &= [Ac]\ \bar{X}c + [Bc]\ \bar{U} \\
\dot{\bar{X}}r &= [Ar]\ \bar{X}r + [Br]\ \bar{U}
\end{aligned}
\qquad (19)
$$

where

$$
\begin{aligned}
\bar{X}c^{T} &= (\, v_1 \quad v_2 \quad \dot{v}_1 \quad \dot{v}_2 \,) \\
\bar{X}r^{T} &= (\, v_3 \quad v_4 \quad \dot{v}_3 \quad \dot{v}_4 \,)
\end{aligned}
\qquad (20)
$$

and where

$$
[Ac] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline & -\omega_i^2 & -2\zeta\omega_i & \end{array}\right] \qquad i = 1,2 \qquad (21)
$$

$$
[Bc] = [\ 0\ \ 0\ \ V_1(x_a)\ \ V_2(x_a)\ ]^{T} \qquad (22)
$$

and where

$$
[Ar] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline & -\omega_i^2 & -2\zeta\omega_i & \end{array}\right] \qquad i = 3,4 \qquad (23)
$$

$$[Br] = [\,0 \;\; 0 \;\; V_1(x_a) \;\; V_2(x_a)\,]^T \tag{24}$$

In addition, the output equations are given by

$$\bar{Y} = [Cc]\,\bar{X}c + [Cr]\,\bar{X}r \tag{25}$$

where

$$[Cc] = [\,V_1(x_s) \;\; V_2(x_s) \;\; 0 \;\; 0\,] \tag{26}$$

$$[Cr] = [\,V_3(x_s) \;\; V_4(x_s) \;\; 0 \;\; 0\,] \tag{27}$$

The quadratic cost function to be minimized is:

$$J = \frac{1}{2}\int_0^{\infty} (\,\bar{X}^T [Q]\,\bar{X} + \bar{U}^T [R]\,\bar{U}\,)\,dt \tag{28}$$

The local matrix Riccati equation solving package OPTCON (Ref 5) solves for the feedback matrix [G] so that Eq (28) is minimized, within the constraints of Eq (27),by the control applied $\bar{U}$:

$$\bar{U} = -\,[G]\,\bar{X} \tag{29}$$

where

$$[G] = [R]^{-1}\,[B\,]^T\,[S] \tag{30}$$

[S] is the solution to the steady-state Ricatti equation:

$$[S][Ac] + [Ac]^T[S] - [S][Bc][R]^{-1}[Bc]^T[S] + [Q] = [0] \tag{31}$$

The OPTCON package solves the Ricatti equation with the appropriate values for [Ac], [Bc], [Q], and [R]. Four cases were considered for [Q]: [Q] = 20, 200, 500, and 6000. For now, we will consider:

$$[Q]=200[I] \quad \text{and} \quad [R] = [I] \tag{32}$$

If full state feedback is to be implemented, a state estimator will be required to produce an estimate of $\bar{X}c$ from the output Y . The deterministic state estimator is of the form:

$$\dot{\hat{X}}(t)c = [Ac]\ \hat{X}(t)c + [Bc]U(t) + [K][\ Y(t) - \hat{Y}(t)\ ] \tag{33}$$

$\hat{X}(t)c$ is the state vector estimate, Y(t) is the sensor output, and $\hat{Y}(t)$ the output corresponding to the estimated state. U(t) is the actuator input. The optimum observer gain matrix [K], can be solved for by the same OPTCON package with the following substitutions:

$$\text{Replace}\quad [Ac] \quad \text{with} \quad [Ac]^T$$

$$[Bc] \quad \text{with} \quad [Cc]^T$$

The output is the matrix of estimator gains, [K], transposed.

The resulting regulator in Figure 2 is reduced to a precomputable set of gains to be applied to the output Y(t) to obtain the desired input to the shaker U(t).

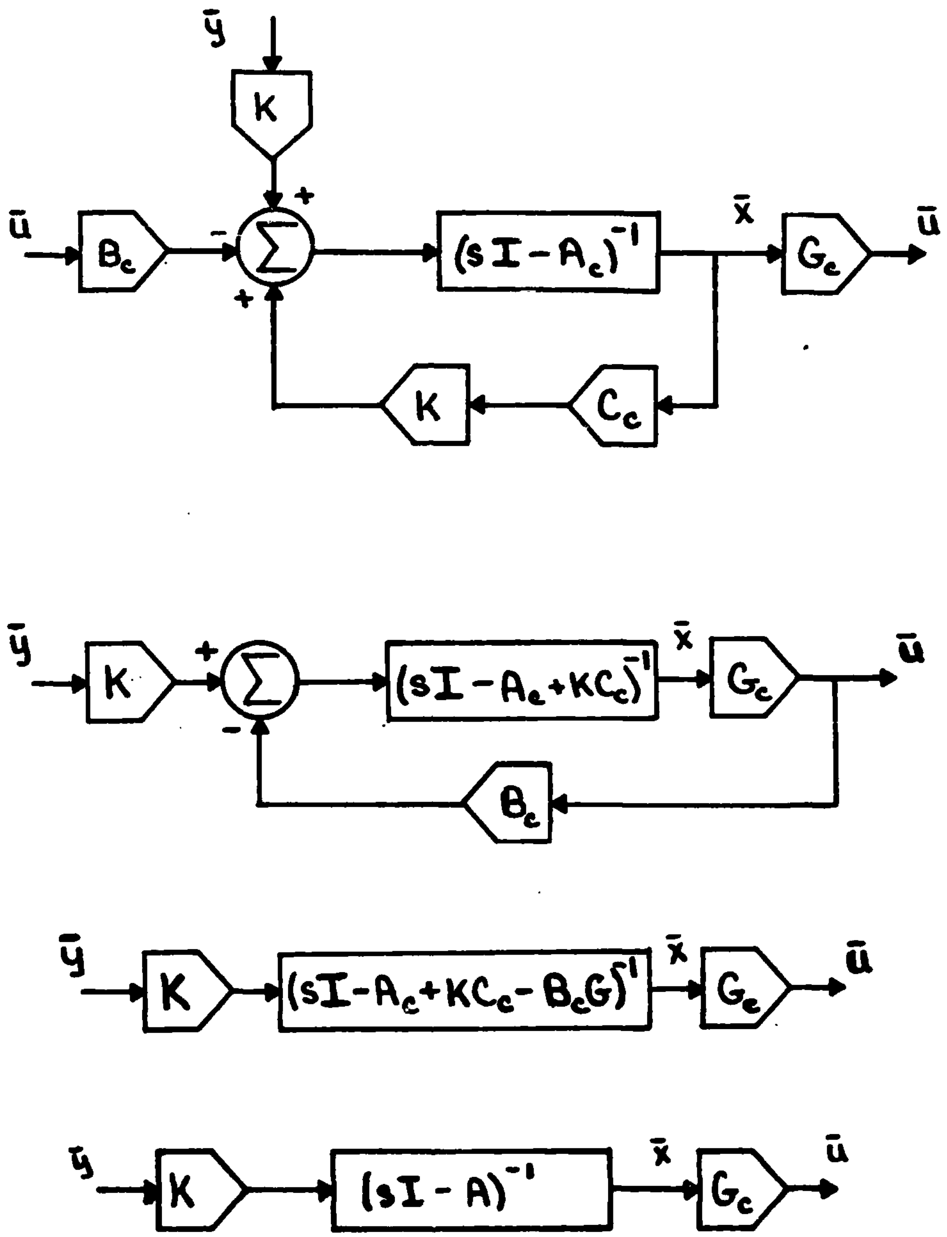


Figure 2. Control Block Diagram

Therefore, the desired control to apply is:

$$U(t) = [G][s[I]-[Ac]-[Bc][G]+[K][Cc]]^{-1} [K] \; Y(t) \qquad (34)$$

The stability of the controller is therefore governed by

the eigenvalues of the matrix [A]. Where [A] is given by

$$[A] = [[Ac] + [Bc][G] - [K][Cc]] \tag{35}$$

The computed natural frequencies, ω_i , which are slightly higher than the measured, are used for the formulation of [Ac]:

$$[Ac] = \left[\begin{array}{cc|cc} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline -7332.12 & 0 & -.8563 & 0 \\ 0 & -55709.0 & 0 & -2.3603 \end{array}\right] \tag{36}$$

$$[Bc] = [\ 0 \quad 0 \quad .10262 \quad .25397\ ]^T \tag{37}$$

$$[Cc] = [\ .307124 \ -.694532 \ 0 \ 0\ ] \tag{38}$$

$$[G] = [\ -2.3698 \quad 7.2801 \quad 8.0764 \quad 7.6288\ ] \tag{39}$$

$$[K] = [\ 11.6250 \ -11.145 \ -23.573 \ -19.485\ ]^T \tag{40}$$

and, as computed (details are also in Appendix 3) [A] is:

$$[A] = \left[\begin{array}{cc|cc} -3.572 & 8.077 & 1.000 & 0 \\ 3.424 & -7.744 & 0 & 1.000 \\ \hline -7325. & -15.62 & -.0275 & .7829 \\ 15.384 & -55720 & 2.051 & -.4228 \end{array}\right] \tag{41}$$

[A] has eigenvalues: -1.800 +/- J 85.63
-4.083 +/- J 235.9

The system eigenvalues are represented by the eigenvalues of [[Ac] +[Bc][G]] and, as computed in Appendix 3, are:

-.8426 +/- 85.624
-2.149 +/- 236.02

As developed by Calico and Janiszewski in Ref 1, the overall system stability with residual modes present is represented in Eq (42). Note that the off-diagonal terms represented by [K][Cr] from Eq (27), are due to observation spillover, and those represented by [Br][G], from Eq (24), are due to control spillover. The actual matrix elements and matrix eigenvalues for various [Q] values are in Appendix 3.

$$\dot{\bar{z}} = \begin{bmatrix} [[Ac]+[Bc][G]] & [[Bc][G]] & [0] \\ [0] & [[Ac]-[K][Cc]] & [[K][Cr]] \\ [[Br][G]] & [[Br][G]] & [Ar] \end{bmatrix} \bar{z} \qquad (42)$$

and the augmented state vector, $\bar{z}$ is:

$$\bar{z} = \left\{ \bar{v}_c^{\,T} , \bar{e} , \bar{v}_r^{\,T} \right\} \qquad (43)$$

where

$$\bar{e}\,(t) = \hat{\bar{v}}_c\,(t) - \bar{v}_c\,(t) \qquad (44)$$

For the sensor and actuator locations chosen, [Cr] and [Br] are given by:

$$[Cr] = [\ 1.0172 \quad -1.2294 \quad 0 \quad 0\ ] \qquad (45)$$

$$[Br] = [\ 0 \quad 0 \quad .4485 \quad .6627\ ] \qquad (46)$$

and [Ar] is:

$$[Ar] = \left[\begin{array}{cc|cc} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \hline -214153 & 0 & -4.6277 & 0 \\ 0 & -585106 & 0 & -7.6492 \end{array}\right] \qquad (47)$$

The equations for the estimator and controller are thus:

$$\dot{\hat{X}} = [A]\,\hat{X} + [K]\,Y \qquad (48)$$

$$U = [G]\,\hat{X} \qquad (49)$$

where Y is the measurement, and U is the control to apply.

Control Implementation. To obtain a discete form of Eq (34), we first integrate both sides:

$$\hat{X}(t) = e^{[A]t}\,\hat{X}(0) + \int_0^t e^{[A](t-\tau)}\,[K]\,Y(\tau)\,d\tau \qquad (50)$$

Or, as derived in Appendix 4,

$$\hat{X}(T) = e^{[A]T}\,\hat{X}(0) + [A]^{-1}\,[e^{[A]T} - [I]]\,[K]\,Y(0) \qquad (51)$$

The result of expanding the exponential into a series, is:

$$\hat{X}(T) = e^{[A]T}\,\hat{X}(0) + [A]^{-1}\,[[A]T + \frac{([A]T)^2}{2!} + \ldots]\,[K]\,Y(0) \qquad (52)$$

In general, for the kth sample period,

$$\hat{X}(T_k) = [[I] + [A]T + \frac{([A]T)^2}{2!} + \ldots]\ \hat{X}(T_{k-1})$$

$$+ T[[I] + \frac{[A]T}{2!} + \frac{([A]T)^2}{3!} + \ldots][K]Y(T_{k-1}) \tag{53}$$

The discrete control to be implemented by the computer is:

$$\hat{X}(T_k) = [H(T)]\ \hat{X}(T_{k-1}) + [F(T)]Y(T_{k-1}) \tag{54}$$

Or simply,

$$\hat{X}_{i+1} = [H]\ \hat{X}_i + [F]Y_i \tag{55}$$

$$U_{i+1} = [G]\ \hat{X}_{i+1} \tag{56}$$

where

$$[H(T)] = [I] + [A]T + \frac{([A]T)^2}{2!} + \frac{([A]T)^3}{3!} + \ldots \tag{57}$$

and

$$[F(T)] = T[[I] + \frac{[A]T}{2!} + \frac{([A]T)^2}{3!} + \ldots][K] \tag{58}$$

Using a sample period of 16 clock ticks (clicks) or about

$$T = .008 \text{ sec}$$

For the two mode model,

$$[H] = \begin{bmatrix} .7513 & .02427 & .007287 & .0001933 \\ .01078 & -.3220 & .0001208 & .003964 \\ -53.38 & -2.316 & .7765 & -.001432 \\ -4.493 & -220.9 & -.005108 & -.2936 \end{bmatrix} \qquad (59)$$

$$[F] = \begin{bmatrix} .08209 \\ -.04310 \\ -2.688 \\ 14.14 \end{bmatrix} \qquad (60)$$

Due to the limited floating point capacity of the single board computer, these matrix multiplications must be carried out in integer arithmetic to adequately follow the arriving frequencies at the sensor. Note that [H] contains a broad range of values among its elements. The range is so broad that to use the matricies as is would cause the computed values to exceed the maximum value allowed in signed 16-bit integer arithmetic. Thus Eq (55) is carefully scaled:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix} = \begin{bmatrix} 10\ x_1 \\ 10\ x_2 \\ .1\ x_3 \\ .1\ x_4 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{bmatrix} = \begin{bmatrix} 10\ f_1 \\ 10\ f_2 \\ .1\ f_3 \\ .1\ f_4 \end{bmatrix} = \begin{bmatrix} .8209 \\ -.4310 \\ -.2688 \\ -1.414 \end{bmatrix} \qquad (61)$$

Where ξ can be thought of as a new "pseudostate" vector. Now Eqs (55) and (56) become:

$$\begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_{i+1} = \begin{bmatrix} .7513 & .0243 & .0073 & .0002 \\ .0108 & -.3220 & .0001 & .0040 \\ -53.38 & -2.316 & .7765 & -.0014 \\ -4.493 & -220.9 & -.0051 & -.2936 \end{bmatrix} \begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_i + \begin{bmatrix} .1\eta_1 \\ .1\eta_2 \\ 10\eta_3 \\ 10\eta_4 \end{bmatrix} Y \quad (62)$$

$$U_{i+1} = [-2.3698 \quad 7.2801 \quad 8.0764 \quad 7.6288] \begin{bmatrix} .1\xi_1 \\ .1\xi_2 \\ 10\xi_3 \\ 10\xi_4 \end{bmatrix}_{i+1} \quad (63)$$

Or,

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} = \begin{bmatrix} .7513 & .0243 & .7287 & .0193 \\ .0108 & -.3220 & .0121 & .3964 \\ -.5338 & -.0232 & .7765 & -.0014 \\ -.0449 & -2.209 & -.0051 & -.2936 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_i + \begin{bmatrix} .8209 \\ -.4310 \\ -.2688 \\ 1.414 \end{bmatrix} Y_i \quad (64)$$

$$U_{i+1} = [-.2370 \quad .7280. \quad 80.76 \quad 76.24] \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} \quad (65)$$

To make these equations integer valued, multiply [H] and [F] by a factor of 128, and divide $\bar{\xi}'_{i+1}$ by 128 when complete. Thus we define a new pseudostate vector, $\bar{\xi}'$:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}'_{i+1} = \begin{bmatrix} 96 & 3 & 93 & 2 \\ 1 & -41 & 2 & 51 \\ -68 & -3 & 99 & 0 \\ -6 & -283 & -1 & -38 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}'_{i} + \begin{bmatrix} 105 \\ -55 \\ -34 \\ 181 \end{bmatrix} Y_i \tag{66}$$

Now the original pseudostate vector is:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} = \frac{1}{128} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}'_{i+1} \tag{67}$$

and the control to apply over the next interval is:

$$U_{i+1} = [0 \quad 1 \quad 81 \quad 76] \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix}_{i+1} \tag{68}$$

Thus the control calculations reduce to a fairly simple set of multiplies and divides in the actual algorithm (Appendix 5).

Sensitivity Analysis. Sample calculations indicate that these equations will not exceed the maximum integer value of 2exp15 as long as the measurement rangeis constrained to integers with $Yi: -100<Yi<+100$.

The analog to digital converter is set up such that a linear relationship exists over the range Vin: $-10v<Vin<+10v$ where:

Vin = Voltage to the A/D board

Din = Digitized value of input voltage

so that

$$Din = (Vin+10) \times 204.8 \tag{69}$$

Thus for:

$$\begin{aligned} Vin &= -10 \Rightarrow Din = 0 \\ Vin &= 0 \Rightarrow Din = 2048 \\ Vin &= +10 \Rightarrow Din = 4096 \end{aligned} \tag{70}$$

Now defining $In = Din - 2048$ (71)

The relationship between Vin and In is:

$$In=204.8 \times Vin \tag{72}$$

In our digital calculations, Yi is the measurement represented by In. Since $Yi: -100<Yi<+100$, the range of In

is In: $-100<In<+100$. This restricts Vin to:

$$\text{Vin: } -.4883\text{v} < \text{Vin} < +.4883\text{v} \tag{73}$$

Note that Yi=100 represents some scaling factor(SF) times the position in nondimensional length units (NL=61.5"). The maximum measured deflection is $|.0615"|$ yielding:

$$100 \longleftrightarrow .0615" \text{ or } .001 \text{ NL}$$

$$\text{SF} = 10\text{exp}5 \tag{74}$$

So using the maximum voltage of .4883v we obtain a desired sensitivity of:

$$.4883/.001 \text{ (V/NL)} = 488.3 \text{ (V/NL)}$$

$$488.3\text{(V/NL)} \times 1000 \text{ (mv/V)} = 4.883 \times 10\text{exp}5 \text{ (mv/NL)}$$

$$4.883 \times 10\text{exp}5 \text{ (mv/NL)}/61.5 \text{ (in/NL)}$$

$$7939.84 \text{ peakmv/in} \tag{75}$$

The accelerometer sensitivity is calibrated as:

$$\begin{array}{c} 11.69 \text{ mv/g at 10hz} \\ 11.99 \text{ mv/g at 30hz} \end{array} \tag{76}$$

Since the first and second natural frequencies have the same order of magnitude contributions at the chosen sensor location, a sensitivity of 11.84 peak millivolts per g will be assumed. The acceleration signal is fed to the vibration

meter. Since the meter requires an input sensitivity of 10 mv(rms) per g(rms), a gain of 1.194 is applied to the acceleration signal before the integration takes place. After proper calibration, the meters display acceleration, velocity, and displacement, and the peak to peak displacement signal is displayed on an rms voltmeter. The desired sensitivity of 5614 mv(rms) per inch (peak displacement) was obtained by attenuating the displacement signal by .1671.

The output of the digital to analog board is proportional to the integer value sent to it (Vout). The linear relationship isthe same as for the analog input. We recall that since the scale factor is 10exp5 and therefore the output is internally divided by 128 to keep within the allowable analog output integer range OUT:-2048<OUT<+2048 , the force desired is in lbf x 781.25. Therefore, if the value (OUT) computed is 78,the desired force is 0.1 lbf. A desired force of .00128 lbf corresponds directly to 10/2048 volts, or 4.8828 mv. The D/A board output sensitivity is therefore:

$$\frac{4.8828}{.00128} \frac{\text{mv}}{\text{lbf}} \quad \text{or} \quad 3814.7 \text{ mv/lbf} \tag{77}$$

The impedance head between the shaker and beam measures force with a sensitivity of 557 mv(peak)/lbf. The following diagram functionally depicts the sensitivity matching which must occur prior to force input to the beam after being attenuated by a factor of PS3 (potentiometer #3 setting).

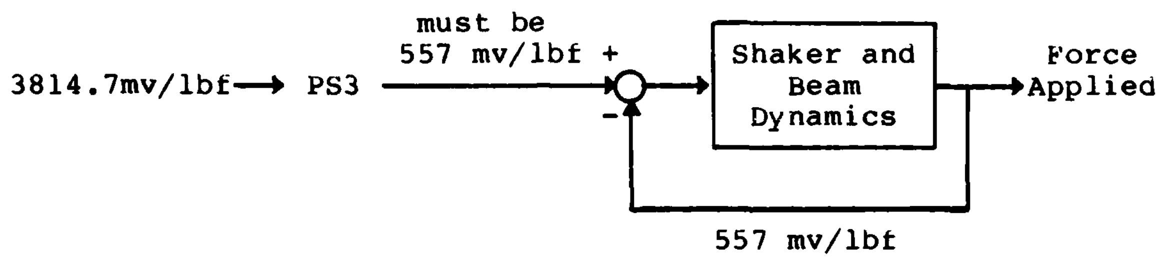


Figure 3. Actuator Sensitivity Matching.

From Figure 3 it is clear that the output force signal must be attenuated by:

$$PS3 = \frac{557}{3814.7} = 0.1460 \qquad (78)$$

RESULTS/CONCLUSIONS

Modal Identification. The results of the sine dwell modal identification (Figures 4 through 7) and the spectrum analysis (Figures 8 through 10) are compared to the computed values in Table I. The ability to consistantly excite the beam's first mode, using the sine dwell technique, was limited by the frequency drift in the function generator. Also, nonlinearities were discovered when too much force was applied by the shaker. As expected, when over excited, the response peak is nolonger symmetric. Also, Figure 11 graphically depicts how approaching the natural frequency from lower frequencies yields drastically different results than when approached from above when nonlinearities are present.

There are basicly four modeling errors: the unmodelled accelerometer mass (2gm), shaker core mass (341gm), the inability to obtain perfectly fixed end conditions, and the passive damping due to the shaker. The first three will lower the measured natural frequencies as shown in Table I. The damping due to the shaker supports, however was not noticeable until the control experiment results were examined.

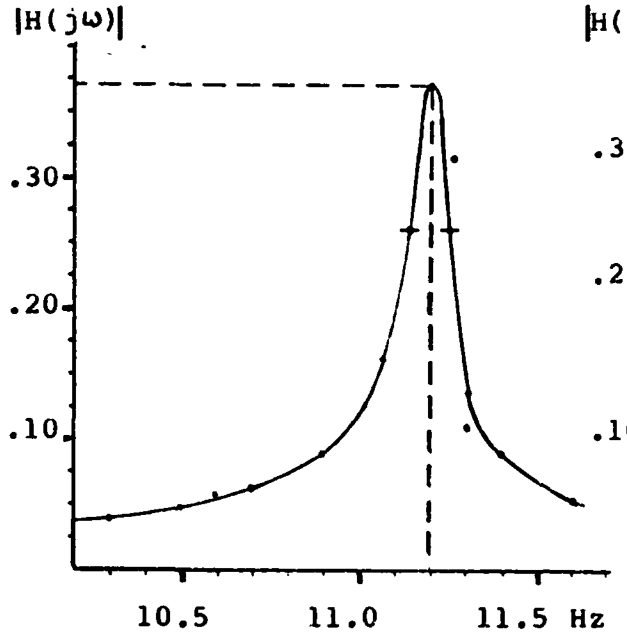


Figure 4. Mode 1
Sine Dwell Identification.

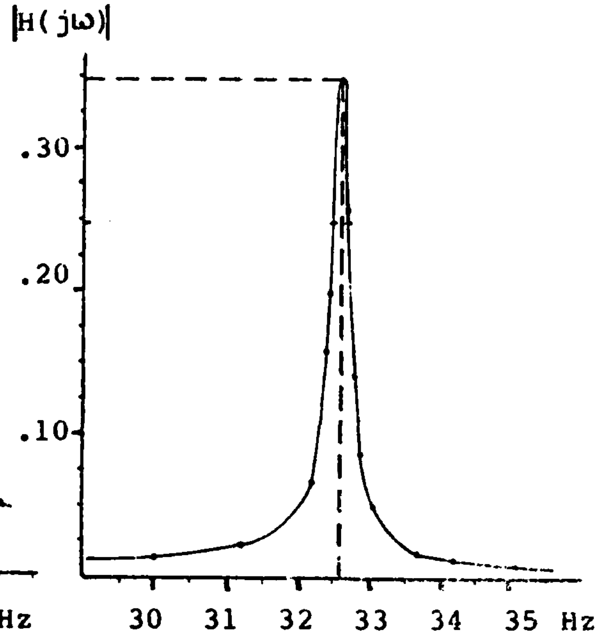


Figure 5. Mode 2
Sine Dwell Identification.

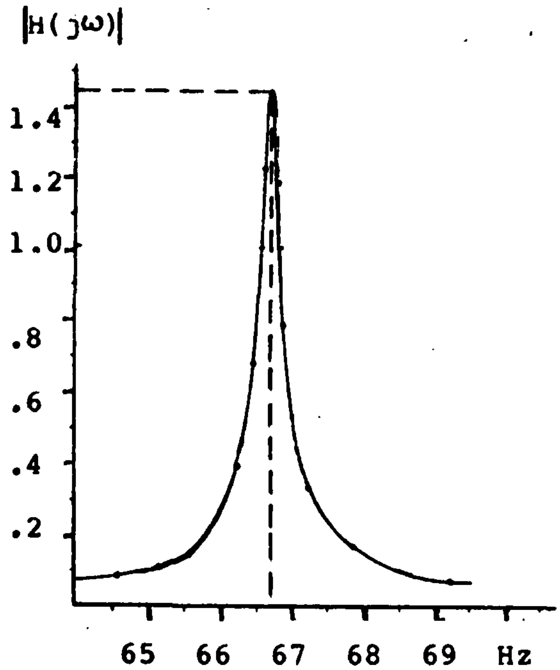


Figure 6. Mode 3
Sine Dwell Identification.

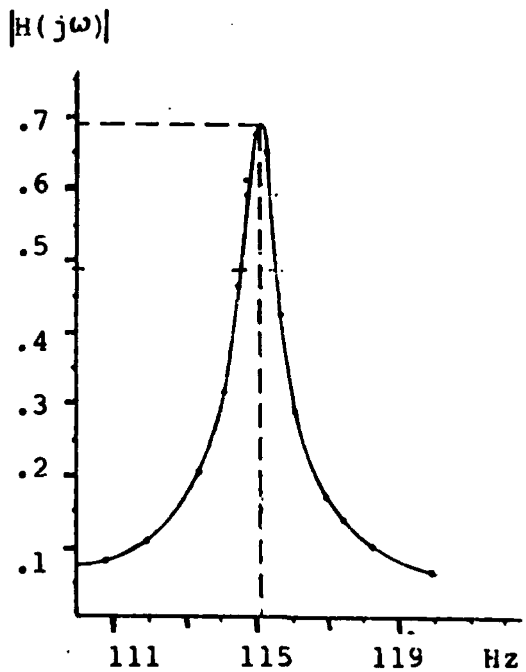


Figure 7. Mode 4
Sine Dwell Identification.

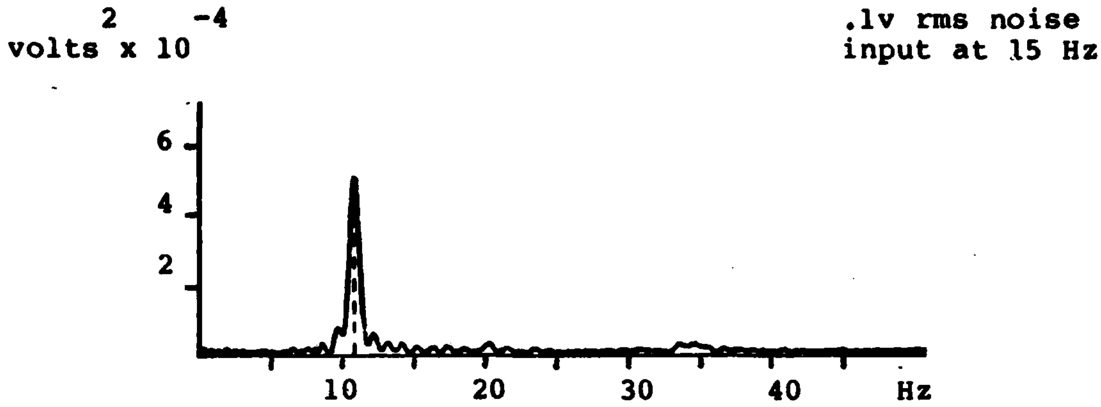


Figure 8. Mode 1 Output Spectrum.

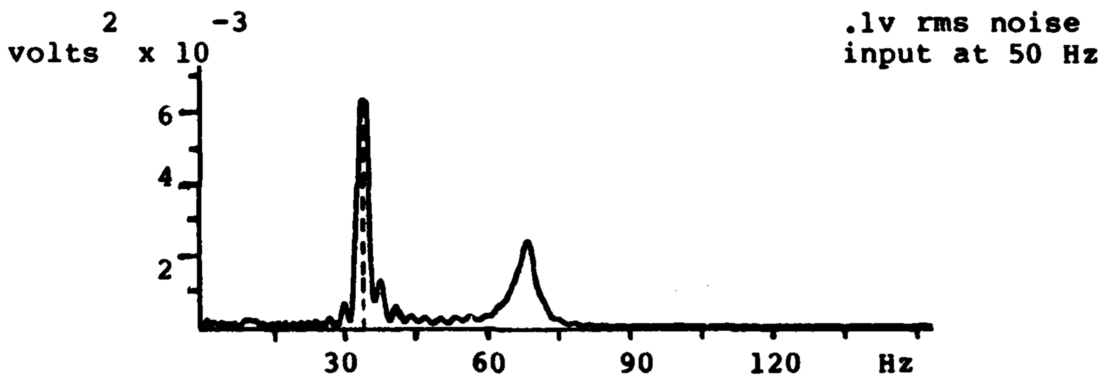


Figure 9. Mode 2 Output Spectrum.

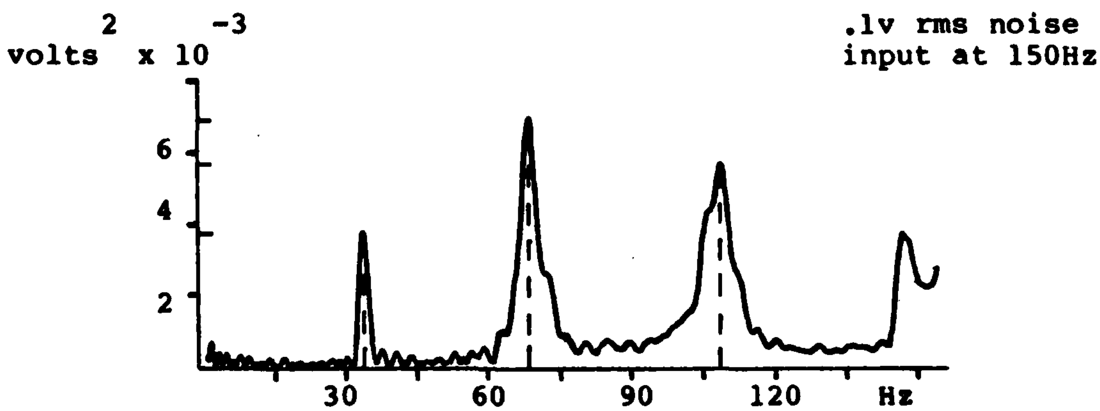


Figure 10. Output Spectrum
Modes 2,3, and 4 Identified.

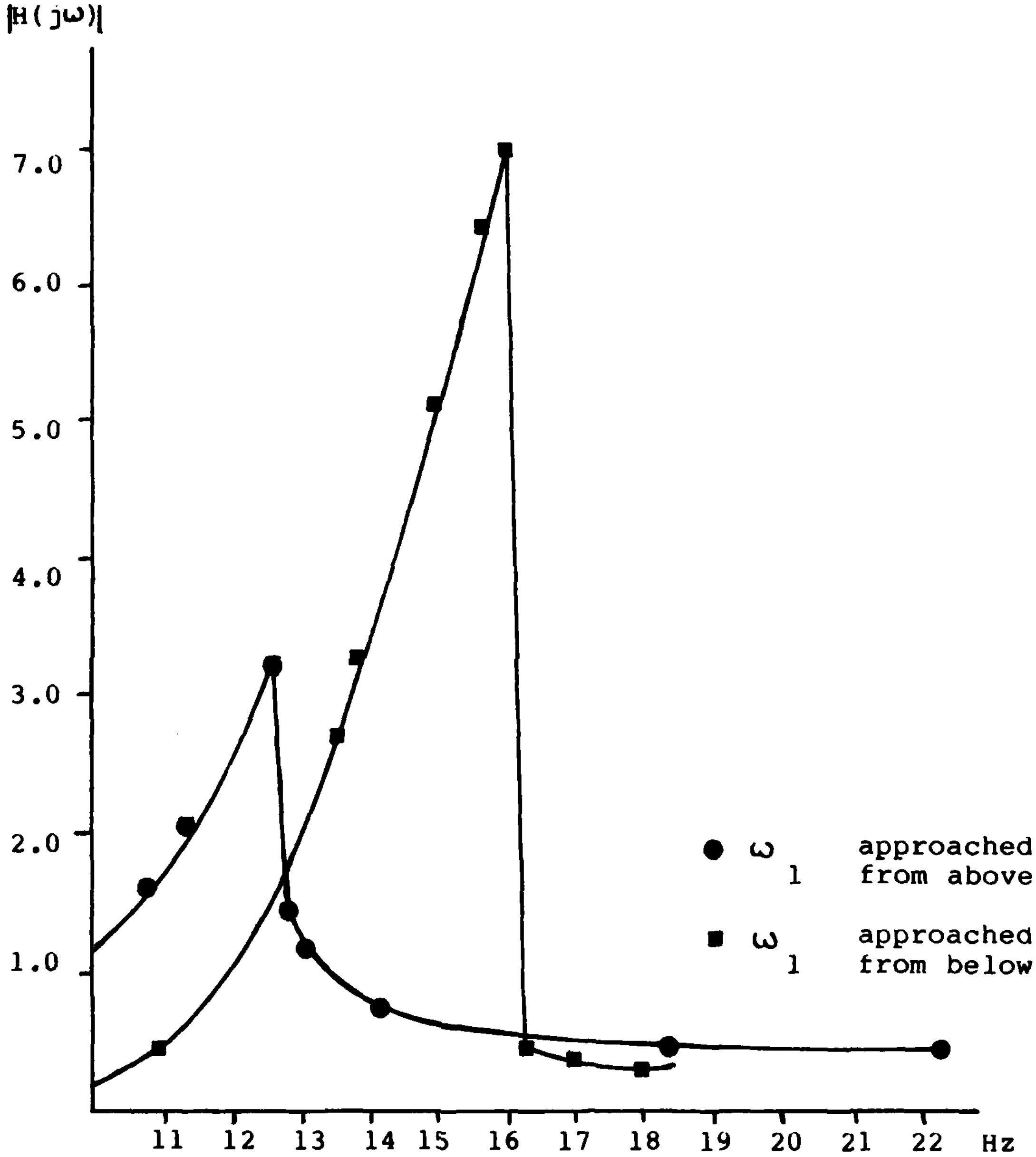


Figure 11. Mode 1 Nonlinear Beam Response.

Table I. Modal Parameters.

	Mode 1	Mode 2	Mode 3	Mode 4
Natural Frequencies-ω_i (Hz)				
Computed	13.63	37.57	73.65	121.74
Sine Dwell	11.2	32.55	66.7	115.1
Spectral Analysis	11.2	35.3	69	109
Assumed in Model	13.63	37.57	73.65	121.74
Damping Ratio (ζ_i)				
Sine Dwell	.0053	.0031	.0019	.0043
Assumed in Model	.005	.005	.005	.005

Software Development. The main emphasis in the software developed was decreasing the cycle time for each control output. Both the measurement sampling and the control output were performed in the same program loop. Thus, sampling rate drove both the observer and controller sensitivity. For a two mode model, it was desired to obtain at least 5 samples per cycle. Signed 16 bit integer arithmetic kept the computation time down. The system was upgraded from 2.5mHz to 5mHz operation and assembly language instructions were optimized. Only four samples per cycle on the second mode were achieved at a sampling rate of 125Hz on the optimized assembly language subroutine (Appendix 5). When it was determined that the sampling rate could not be increased further without obtaining another processor or going to a single mode approximation, the two mode control was attempted.

The Control Experiment. The data obtained from the static deflection testing was stored on disk, then plotted (as in Figures 19 through 22) and tabulated in Appendix 5. The spectral analyzer output a plot of the acceleration PSD. The half power method was used again to compute the measured damping for each mode. The expected pole migration, obtained from the eigenvalues of Eq 42, and the pole migration actually obtained is presented in Figures 12 and 13. The differences in measured natural frequencies seen in Figures 14 through 18 as compared to those calculated in the modal parameter section are due to the additional shaker used to input the noise the noise disturbance. The passive damping by the shaker is evident in the root migration for each mode. The computed movement, including the effect of the residuals, produced only slightly stable roots, while the actual roots became more highly damped with the force loop closed around the shaker. Note that no change occured for the first mode between the force loop closed condition and the control applied condition. The second mode became more lightly damped however. The residual modes were expected to cause a more lightly damped set of modes of vibration, but their actual effect is masked by this passive damping. The third mode damping increased slightly, and the fourth mode was significantly damped. The damping of the third and fourth modes was not due to the control applied, and Figures 14, 15 and 16 clearly demonstrate that it was due to the shaker dynamics.

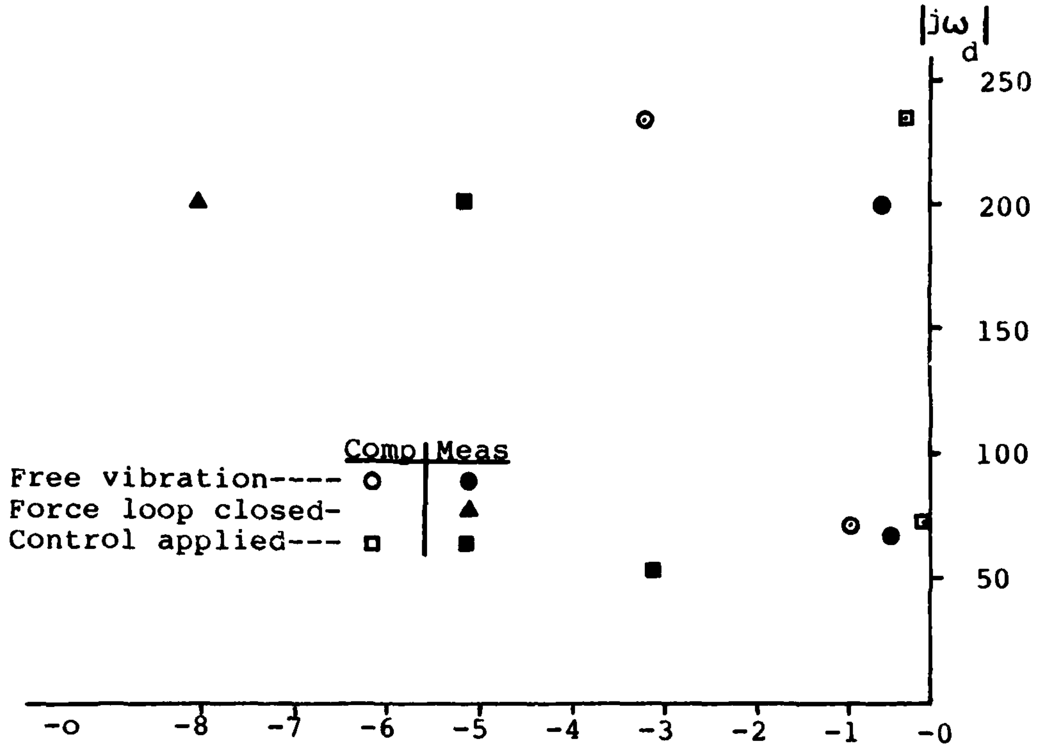


Figure 12. System Pole Movement
Modes 1 and 2.

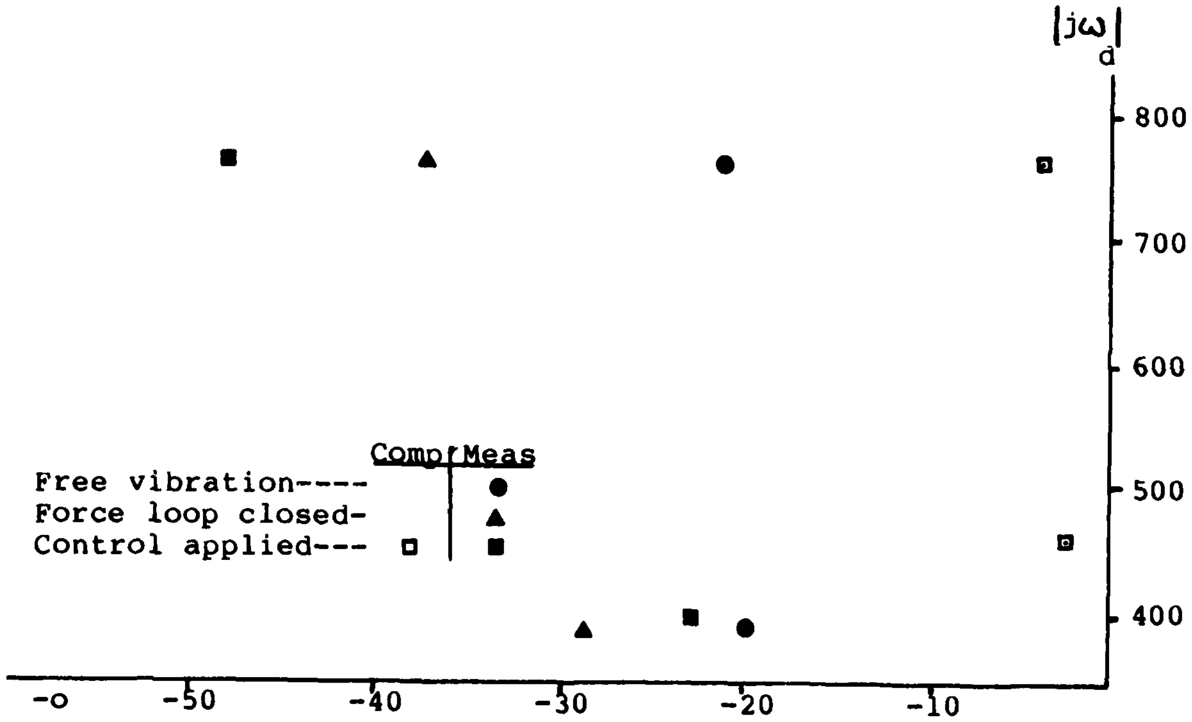


Figure 13. System Pole Movement
Modes 3 and 4.

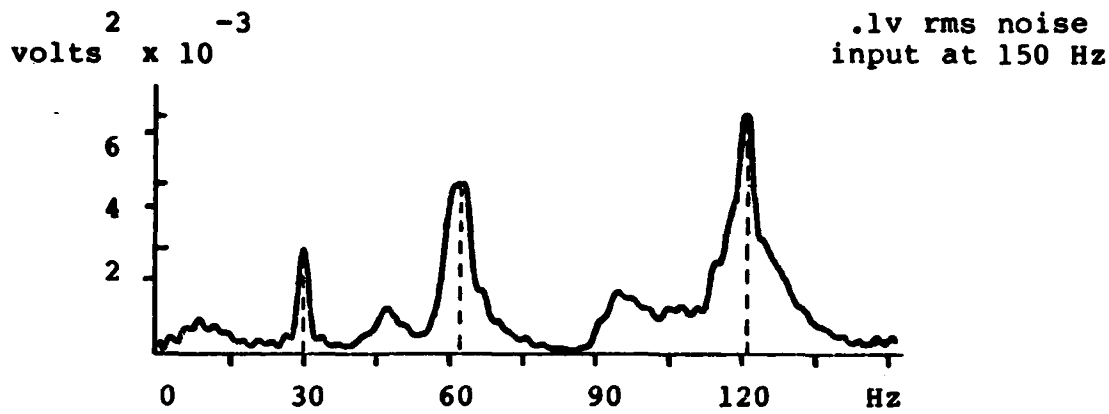


Figure 14. Modes 2,3, and 4
Free Vibration.

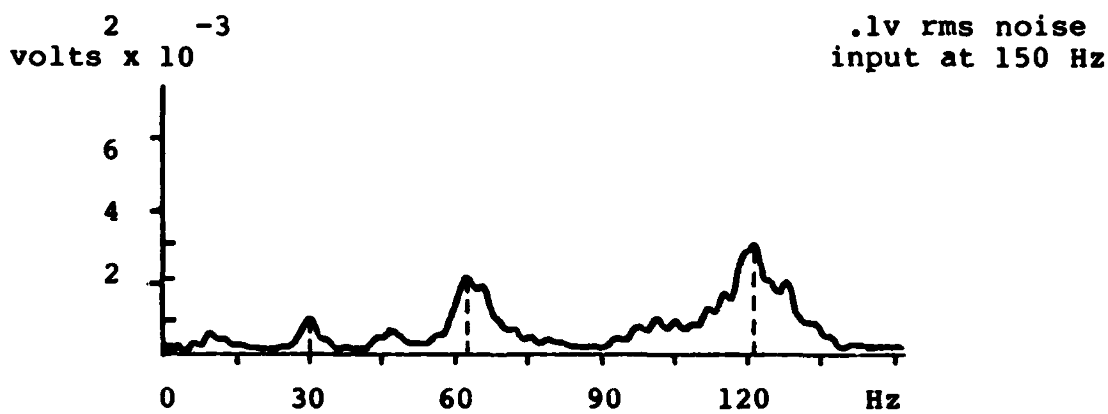


Figure 15. Modes 2,3, and 4
Force Loop Closed.

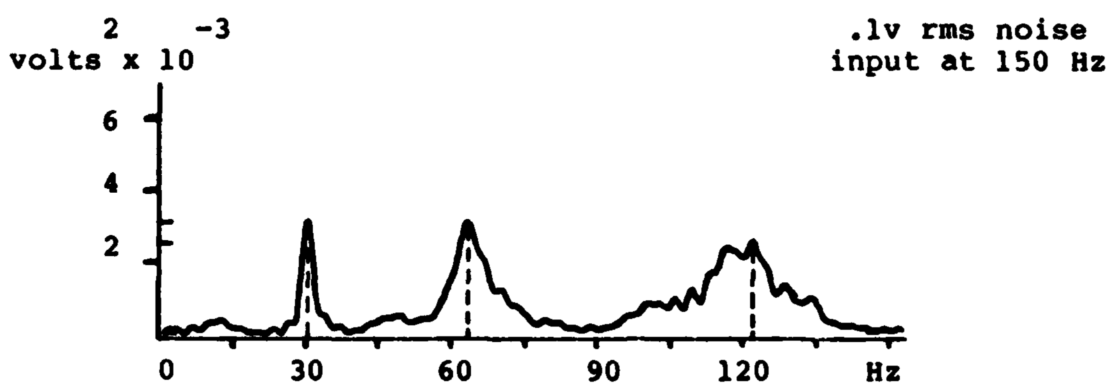


Figure 16. Modes 2,3, and 4
Control Applied.

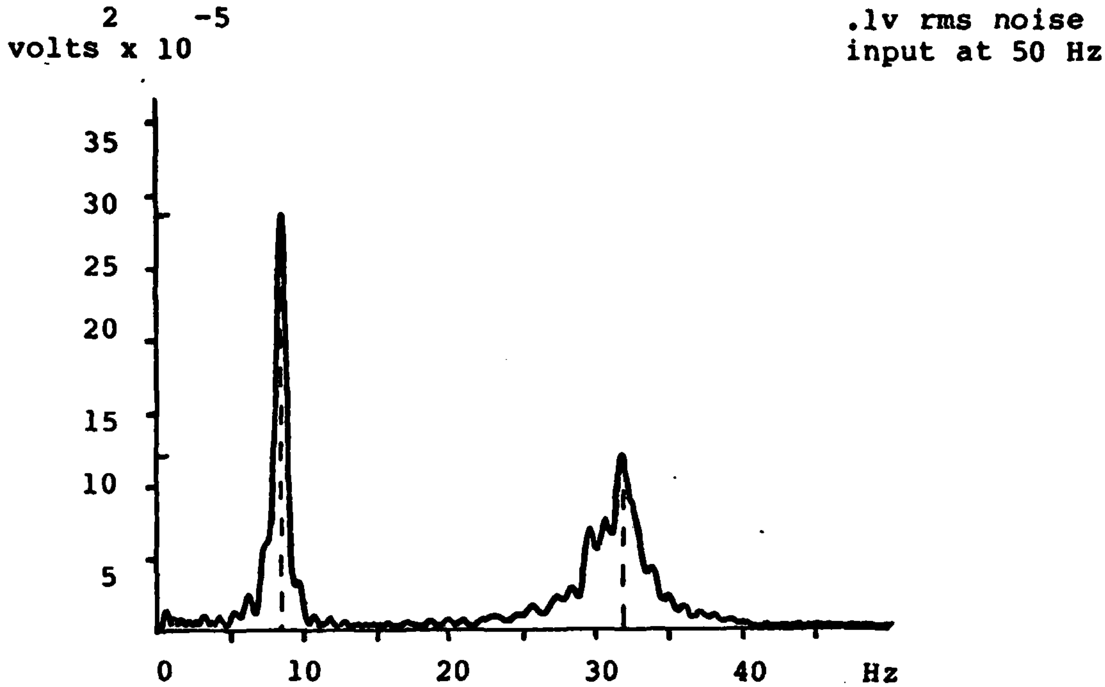


Figure 17. Modes 1 and 2
Force Loop Closed.

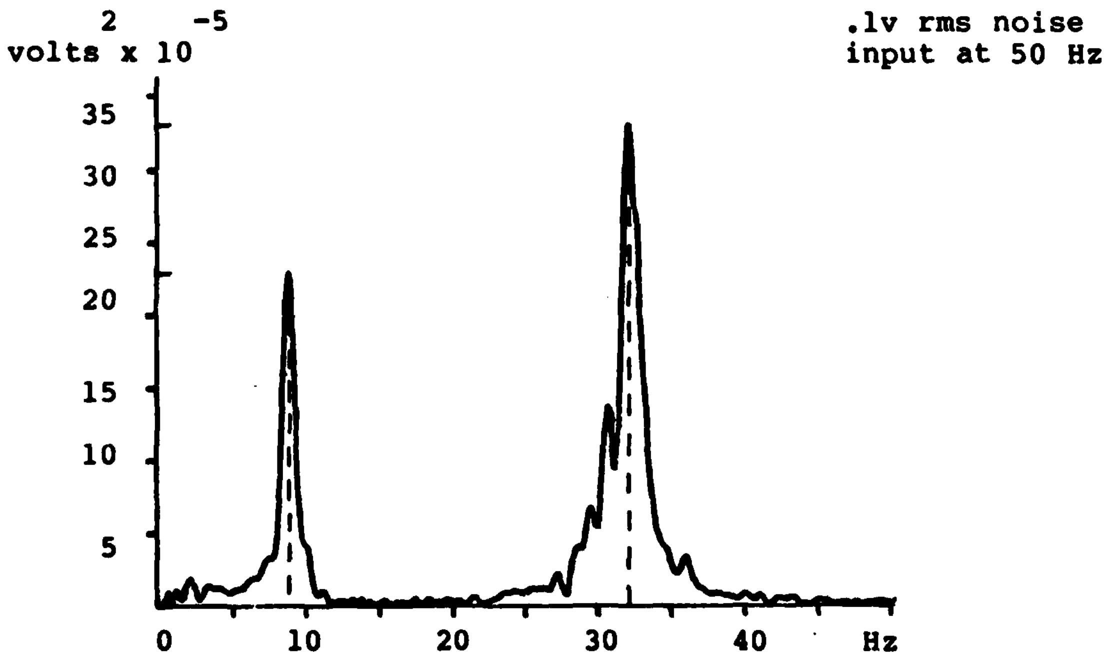


Figure 18. Modes 1 and 2
Control Applied.

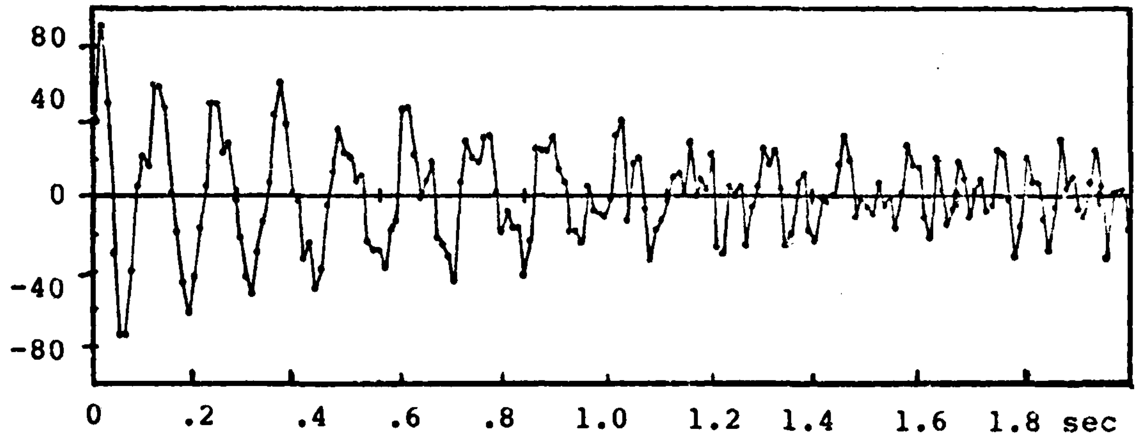


Figure 19. Mode 1 Estimate Force Loop Closed.

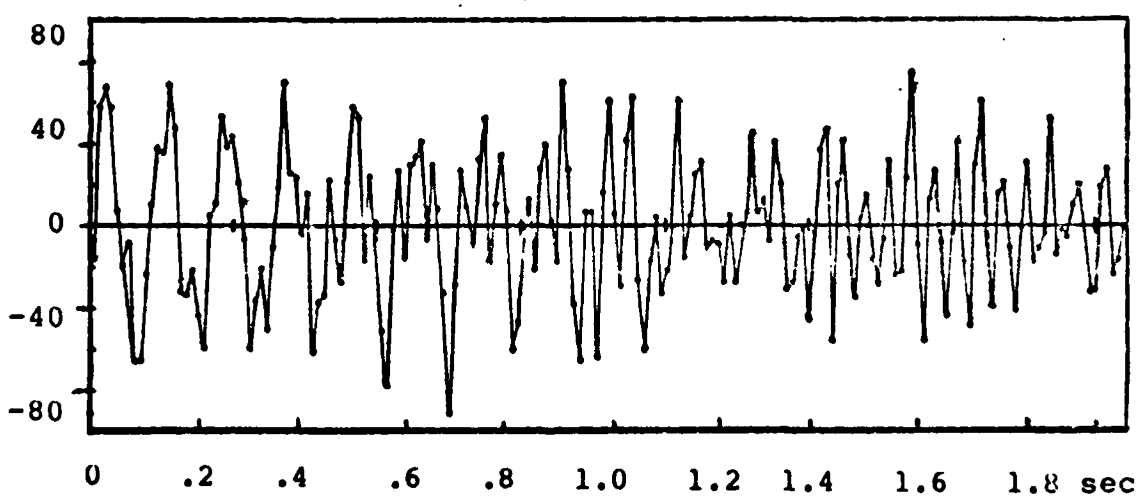


Figure 20. Mode 1 Estimate Control Applied.

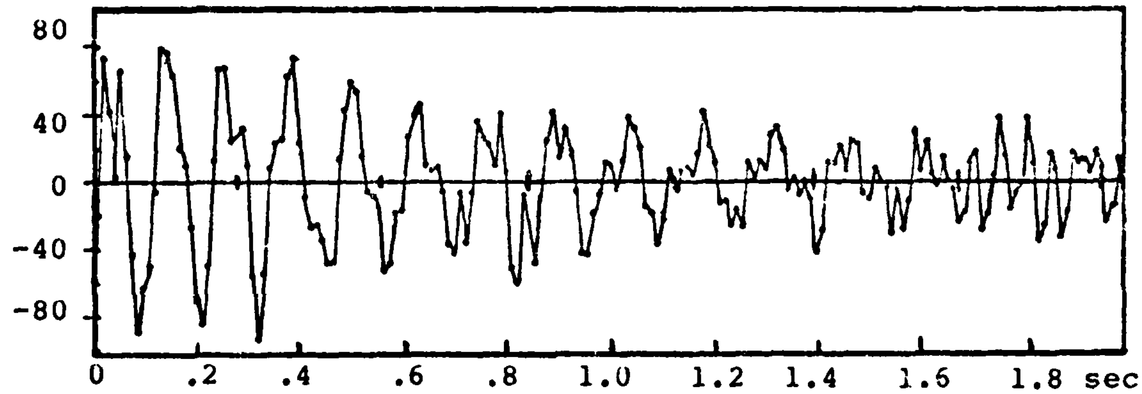


Figure 21. Mode 2 Estimate Force Loop Closed.

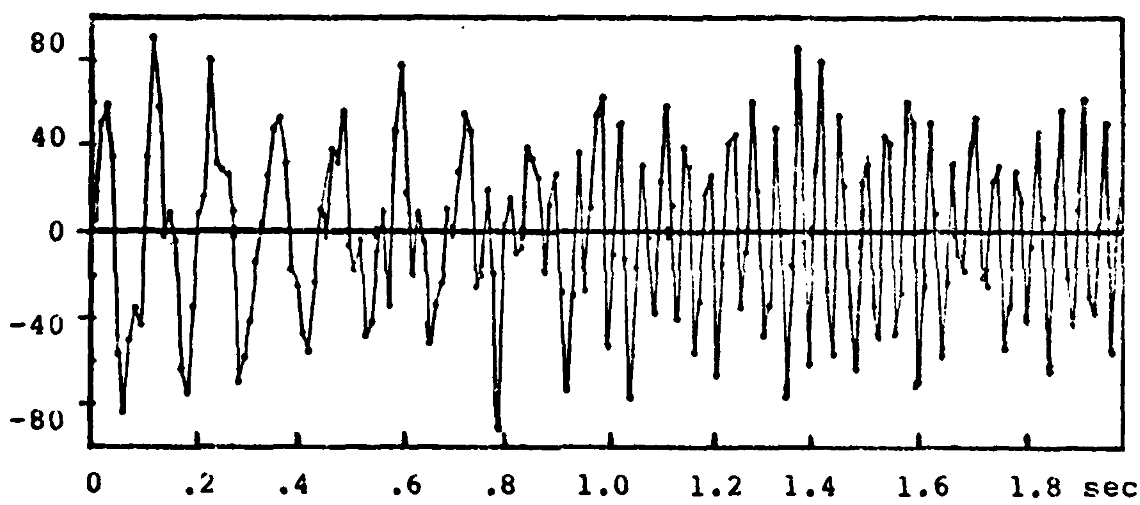


Figure 22. Mode 2 Estimate Control Applied.

The damping of the third and fourth modes was anticipated as Herrick (Ref 3) discovered similar problems where the shaker acted as a passive dashpot when used in this capacity. He found this to be the result of the shaker's flexure supports and restored the beam's resonant behavior by a positive velocity feedback loop around the shaker.

The time responses of the estimate of mode 1 (Fig 19 and 20) for Q=200 show that the more lightly damped higher modes predominate shortly after control is applied. Similarly, for the estimate of mode 2 (Fig 21 and 22), the second mode quickly predominates and a much cleaner estimate of the modal amplitudes is produced for this reason.

In summary, the effect of this controller was to slightly damp the first mode and negatively damp the second. The third and fourth modes were damped, however this is attributed to the passive damping of the shaker. Limitations on the control applied include sampling rate, truncation errors due to scaling and use of integer arithmetic, a lack of a positive velociy feedback loop around the shaker, and a lack of phase compensation.

RECOMMENDATIONS

The experience gained in implementation of optimal control algorithms in this experiment has helped to identify some sensitive areas which may affect performance.

The sensor and actuator locations are very important. Although the sensor did well at the location chosen, the actuator did poorly due to its lack of control authority over the first mode. The optimum actuator position is dependent on the relative cost associated with not controlling each mode. Therefore, for this experiment the actuator should be located nearer the center of the beam. In addition, the diagonal elements of [Q] should be weighted to reflect these costs when calculating the optimum controller and observer gain matricies.

Shaker damping was a significant factor inthe degraded controller performance and should be compensated for using a velocity feedback path around the shaker. An impedance head which outputs both acceleration and force simultaneously is ideal for this implementation.

The need for faster computation speed is obvious; however no matter what hardware constraints are imposed, the control algorithm will have to be optimized to yield acceptable computation rates and accuracy. A working knowledge of the specific machine code utilized will be required for this.

Finally, new methods for exciting the beam without the addition of a second actuator, such as acoustic vibration and the use of a load cell equipped hammer, should be examined.

BIBLIOGRAPHY

1. Calico, R.A. and Janiszewski, A.M. Control of a Flexible Satellite Via Observation Spillover. WPAFB,OH: AFIT,1978.

2. Schaechter, D. Hardware Demonstration of Flexible Beam Control. Pasadena,CA: California Institute of Technology, Jet Propulsion Lab, 1980.

3. Herrick, D.,Canavin, J., and Strunce, R. An Experimental Investigation of Modern Modal Control.Cambridge,MA:Charles Stark Draper Lab, 1979.

4. Hungerford, J.B. Active Control of Bending Vibration in a Cantilever Beam. WPAFB, OH: AFIT.

5. Wilt, Mirmak, and Ray. OPTCON: Solution of the Linear Quadratic Optimal Control Problem. WPAFB, OH: 1982.

6. Balas, M.J. "Active Control of Flexible Systems." AIAA Symposium on Dynamics and Control of Large Flexible Spacecraft, Blacksburg, VA: 1977.

7. Meirovich, L. Elements of Vibrational Analysis. NewYork: Mcgraw-Hill, Inc. 1975.

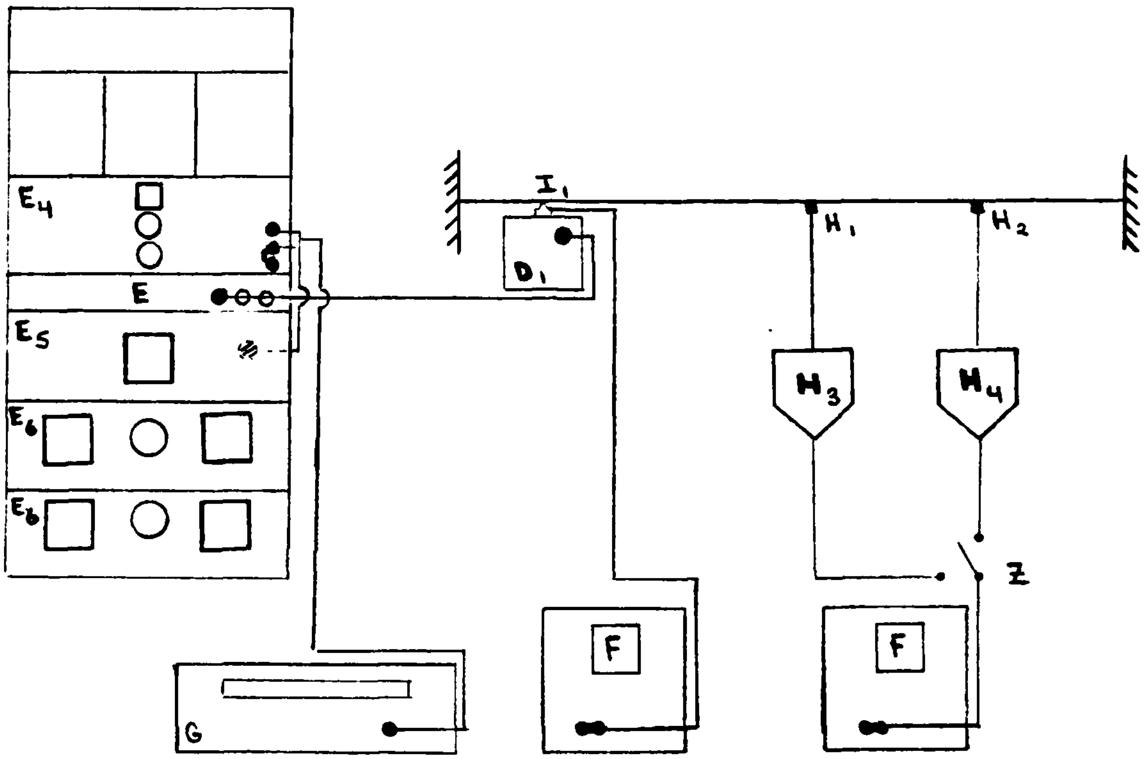
8. Nichols, E. A. Nichols, J. C., Rony, P. R., Z-80 Microprocessor Programming and Interfacing, Book 1. Indianapolis, Indiana: Howard W. Sams and Co.Inc., 1981.

9. Osborne, A. An Introduction to Microprocomputers, Vol 1, Basic Concepts. Berkley, Ca: Osborne/McGraw-Hill, 1980.

APPENDICES

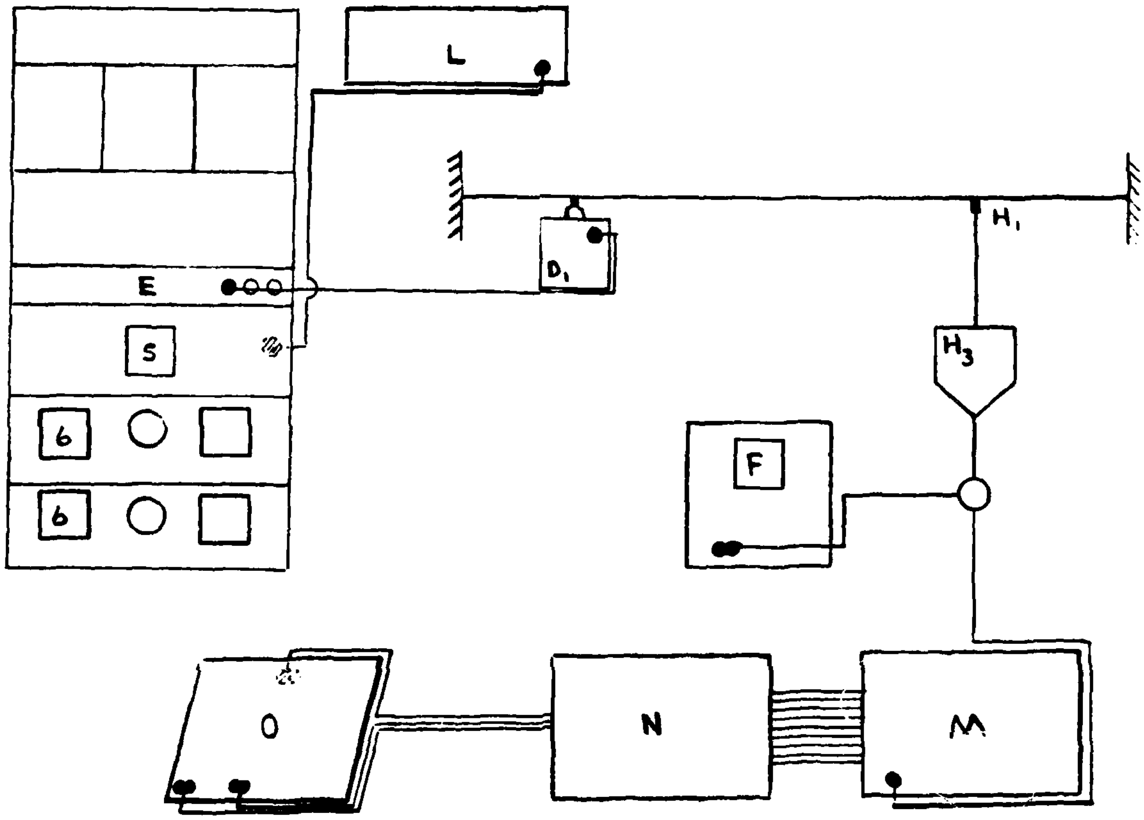
Appendix 1

Equipment Configurations



D1	- Shaker	Detune Clip-Full Up.
E4	- Low Frequency Function Generator	Function-Sine, Amp<10.
E5	- Power Amplifier	Cathode-1.
E6	- DC Power Supply	H.V.-ON, DC Amps=200.
F	- True RMS Voltmeters	Use, Meter.
G	- Universal Counter-Timer	AC Input, Func.-Period Time- N=10exp2.
H1	- Accelerometer	&Elect.Iso. Mechanism.
H3	- Battery Power Unit	Gain=100.
I	- Impedance Head	Use Force Output.
Z	- Electrical Connection	Beam Center-Modes 1&3. Offset-Modes 2&4.

Figure 23. Sine Dwell
Modal Parameter Identification



D1,E,F,H1,H3............................Same as for Figure 23.
L - Noise Generator......Seq.Length-Infinite, Gaussian Output.
M - Correlator...........Func.-Autocor.,Averaging-Exponential.
Dither-ON,Delay Offset-0,Interpolation-On,Input-A-AC.
N - Spectrum Display.....Input-1,Disp-Spectrum,Real,Window-Off
Gain-5,Interpolation-Auto,Marker-Off,Vertical-Modulus
Horizontal-Freq.,Phase Shift-0,Cal-Off,Record-scan.
O - X-Y Recorders........Time Base-Off,Sweep Rate-5,Line-On,
Pen-lift,Servo-On;Polarity-X:+RT,Y:+UP;Reponse-X:Slow
Y:Slow;Range-X:1v/in,Y:.5v/in.

Figure 24. Spectrum Analysis
Modal Parameter Identification

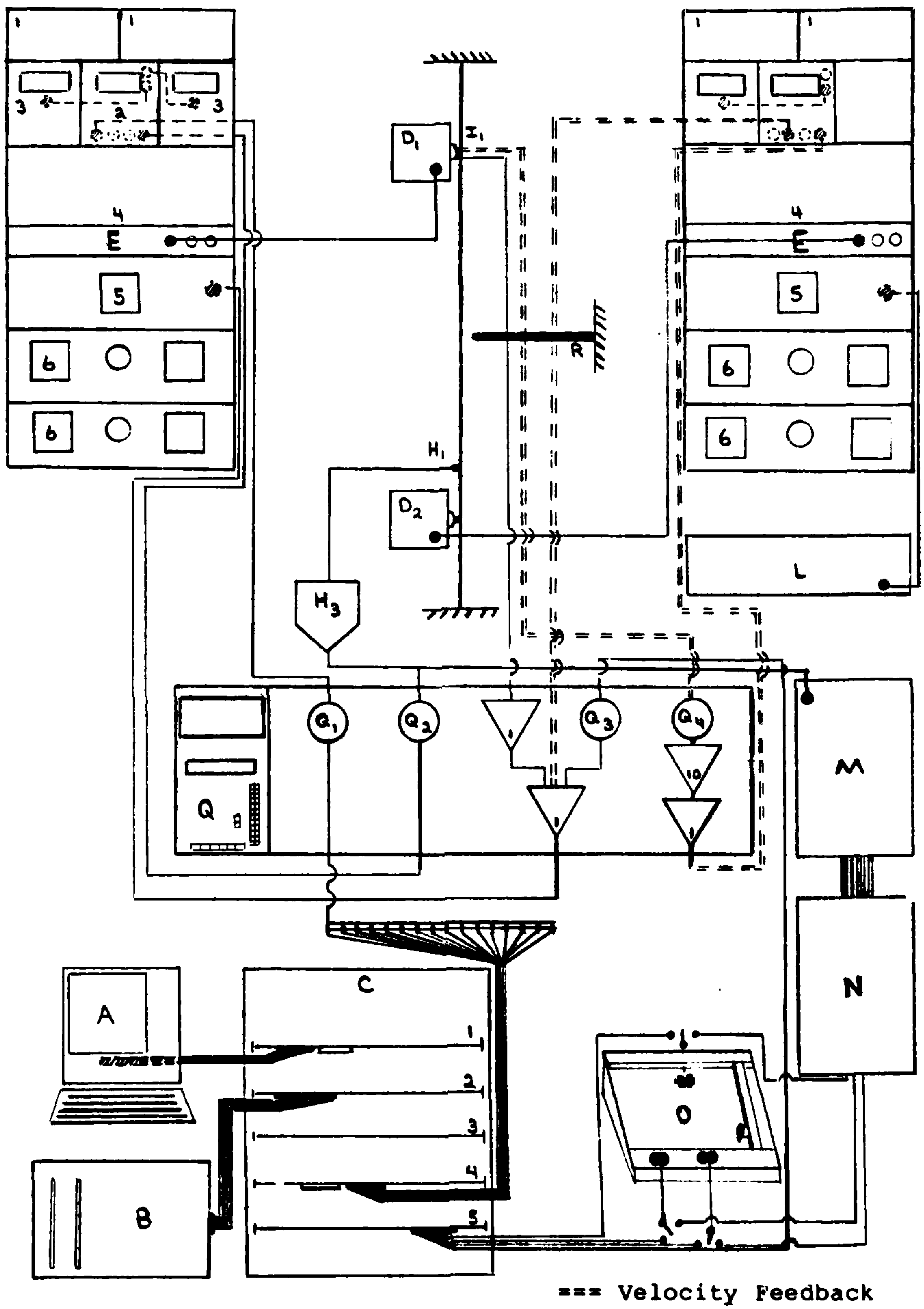


Figure 26. Control Experiment.
(Legend Next Page)

Figure 25 Legend.

A - Video Terminal.
B - 8" Floppy Disk Drive.
C - S-100 Mainframe: 1 - SBC-100: Serial Input/Output to A.
2 - Disk Drive Board.
3 - Memory Board.
4 - A/D Board: Input on Chan 0 from Q1.
5 - D/A Board: Chan 0 - Q3.
Chan 1 - X on plotter.
Chan 2 - Y on plotter.
Chan 3 - PenUp on plotter.
D(1&2) - Shaker........................Same as Figure 23.
E- PortableCabinet:SameasFigure23,except E2-Input from Q2
Out Disp.->Q1
Connect to Q3
H1 - Accelerometer.
H3 - Battery Power Unit.................Gain=10.
I - Impedance Head.
L - Noise Generator.....................Same as Figure 24.
M - Correlator..........................Same " " ".
N - Spectrum Display....................Same " " ".
O - X-Y Recorder: Continuous Vibration Input - Input from N.
Initial Displacement Input - Input from C5.
Q - Analog/Hybrid Computer: Pot. Settings: Q1= .1671
Q2= .1194
Q3= .1460
Q4= .2571
R - Initial Condition Displacement Mechanism: Rod w/wall pivot

LABORATORY EQUIPMENT

A. Heathkit Terminal(#5):Model H19-A - SN 17-43722.

B. Tarbell Floppy Disk Drive:Model VDS-TTD - SN 2267/0482.

C. ECT(Electronic Control Technology)Mainframe MB -10.

1. SBC-100 Single Board Computer - SD Systems
2. Single Density Floppy Disk Interface Board Tarbell - SN 10867.
3. Expandoram III-Expandable Random Access Memory-SD Systems - SN AW 0100160.
4. AIM-12, 12 bit Analog Input Module-Dual Systems Corporation.
5. AOM-12,12 bit 4 Channel S-100 Digital to Analog Converter - Dual Systems Corporation - SN 1039.

D. Shakers - MB Electronics Vibration Test Equipment

1. Model SAC - SN 186.
2. Model SDA - SN 271.

E. Portable Cabinet

1. Accelerometer Integrator/Amplifier MBElectronics-Model N504-SN PS4110 and PS4111.
2. Vibration Meter - MB Electronics - Model N499 SN 168 and SN 151.
3. Vibration Indicator- MB Electronics- Model N497 SN 162 and SN 173.
4. Low Freq Function Generator - Hewlett Packard Model 202A - SN 325-13268 and 4156.
5. 125VA Power Amplifier - MB Electronics Model 2120MB - SN 904 and 913.

6. DC Power Supply - Hewlett Packard - Model712B

SN 002-05035 and SN 002-05037.

SN 002-05082 and SN 002-05083.

F. True RMS Meters - Ballantine Laboratories - Model 320

1. SN 1537(EE Lab).

2. SN 1538(EE Lab).

G. Universal Counter-Timer - Computer Measurements Co. Model 726C - SN 49300/4H5581.

H. I.C.P. Accelerometer-PCB Piezotronics Inc.

1. Model 303A - SN 1935.

2. Model 303A - SN 1934.

3. Battery Power Unit - PCB -Model 480C06 -SN 1247.

4. Battery Power Unit - PCB -Model 480D06 -SN 2062.

I. Impedance Head - Wilcoxon Research

1. Model Z11 - SN 900.

2. Model Z11 - SN 802.

J. Oscilloscope - Tektronics Inc.- Model 116E- SN 002800.

K. DC Power Supply - H.P. - Model 6205B - SN 1949A16663.

L. Noise Generator - H.P. - Model 3722A - SN 1722U01822.

M. Correlator - H.P. - Model3721A- SN 1112A00104.

N. Spectrum Display - H.P. -Model 3720A - SN 1215U00120.

O. X-Y Recorders - H.P. - Model 7045B - SN 2129A00481.

P. S-100 Bus Extender Board-Bob Mullen Computer Products Model TB4 - SN 0281.

Q. TR-48 Analog/Hybrid Computer-EAI- Model 45.117-SN 568.

R. Initial Condition Displacement Mechanism: Rod.

Appendix 2

Normalizing the Eigenvectors

$$\int_0^L V_i^2(x)m\,dx = 1 \qquad (13)$$

where

$$V_i(x) = C_1 \sin(\beta_i x) - C_1 \sinh(\beta_i x) + Z_i C_1 [\cos(\beta_i x) - \cosh(\beta_i x)] \qquad (14)$$

For L = 1, and $\beta_1 = 4.73 \Rightarrow Z_1 = -1.017809$

$\Rightarrow C_1 = .80452$

$\Rightarrow C_2 = -.81885$

$\beta_2 = 7.853 \Rightarrow Z_2 = -.99922$

$\Rightarrow C_1 = .819261$

$\Rightarrow C_2 = -.818622$

$\beta_3 = 10.996 \Rightarrow Z_3 = -1.00003$

$\Rightarrow C_1 = .818953$

$\Rightarrow C_2 = -.81898$

$\beta_4 = 14.1372 \Rightarrow Z_4 = -.999998$

$\Rightarrow C_1 = .827169$

$\Rightarrow C_2 = -.827168$

So that the normalized eigenvectors are:

$$V_1(x) = .80452[\sin(4.73x) - \sinh(4.73x)] + .81885[\cosh(4.73x) - \cos(4.73x)] \quad (17)$$

$$V_2(x) = .81926[\sin(7.853x) - \sinh(7.853x)] + .81862[\cosh(7.853x) - \cos(7.853x)] \quad (18)$$

$$V_3(x) = .81895[\sin(10.996x) - \sinh(10.996x)] + .81898[\cosh(10.996x) - \cos(10.996x)] \quad (13c)$$

$$V_4(x) = .82717[\sin(14.1372x) - \sinh(14.1372x)] + .82717[\cosh(14.1372x) - \cos(14.1372x)] \quad (13d)$$

The values of these mode shapes are then:

	Sensor(x_s = .852698 NL)	Actuator(x_a = .079956 NL)
$V_1(x)$	.3071239	.1026195
$V_2(x)$	-.6945324	.2539699
$V_3(x)$	1.0171641	.448457
$V_4(x)$	-1.229404	.6626658

Appendix 3

Pole Placement Generation and System Eigenvalues

This appendix contains for Q = 20, 200, 500, 6000:

A. OPTCON generated controller and observer gains [G] and $[K]^T$ (labeled feedback matrix in computer output).

B. Closed loop system matrices [[Ac]+[Bc][G]-[k][Cc]] without residuals present and their eigenvalues.

C. Eigenvalues of the closed loop system matrices (with residuals present) of the form:

$$\begin{bmatrix} [[Ac]+[Bc][G]] & [Bc][G] & [0] \\ [0] & [[Ac]-[K][Cc]] & [K][Ccr] \\ [Bcr][G] & [Bcr][G] & [Acr] \end{bmatrix}$$

D. Computed [H], [F], and [G] matrices for computer implementation of $\hat{X}_{i+1} = [H]\hat{X}_i + [F]Y_i$ and

$U_{i+1} = [G]\ \hat{X}_{i+1}$.

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

2.0000E+01	0.	0.	0.
0.	2.0000E+01	0.	0.
0.	0.	2.0000E+01	0.
0.	0.	0.	2.0000E+01

R

1.0000E+00

RICCATI SOLUTION

8.0238E+04	-7.1770E-01	1.3637E-03	-1.7360E-01
-7.1770E-01	2.2375E+05	1.3190E+00	1.7934E-04
1.3637E-03	1.3190E+00	1.0943E+01	-3.5887E-05
-1.7360E-01	1.7934E-04	-3.5887E-05	4.0164E+00

FEEDBACK MATRIX

-4.3949E-02	1.3540E-01	1.1230E+00	1.0200E+00

CLOSED LOOP EIGENVALUES

REAL	IMAGINARY
-.48577E+00	-.85626E+02
-.48577E+00	.85626E+02
-.13097E+01	-.23602E+03
-.13097E+01	.23602E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	-7.3320E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

2.0000E+01	0.	0.	0.
0.	2.0000E+01	0.	0.
0.	0.	2.0000E+01	0.
0.	0.	0.	2.0000E+01

R

1.0000E+00

RICCATI SOLUTION

8.0830E+00	2.7947E-04	-6.9191E+00	-6.3415E+00
2.7947E-04	3.1945E+00	8.3428E-01	-7.5389E+00
-6.9191E+00	8.3428E-01	5.9252E+04	8.7636E+00
-6.3415E+00	-7.5389E+00	8.7636E+00	1.7794E+05

FEEDBACK MATRIX

2.4823E+00	-2.2186E+00	-2.7045E+00	3.2884E+00

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.80934E+00	-.85623E+02
-.80934E+00	.85623E+02
-.19506E+01	-.23602E+03
-.19506E+01	.23602E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

2.0000E+02	0.	0.	0.
0.	2.0000E+02	0.	0.
0.	0.	2.0000E+02	0.
0.	0.	0.	2.0000E+02

R

1.0000E+00

RICCATI SOLUTION

5.7709E+05	-6.4313E+01	1.3256E-02	-9.3362E+00
-6.4313E+01	1.6735E+06	7.0939E+01	1.3194E-03
1.3256E-02	7.0939E+01	7.8710E+01	-3.3003E-03
-9.3362E+00	1.3194E-03	-3.3003E-03	3.0039E+01

FEEDBACK MATRIX

-2.3698E+00	7.2801E+00	8.0764E+00	7.6280E+00

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.21489E+01	-.23602E+03
-.21489E+01	.23602E+03
-.84256E+00	-.85624E+02
-.84256E+00	.85624E+02

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	-7.3321E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

2.0000E+02	0.	0.	0.
0.	2.0000E+02	0.	0.
0.	0.	2.0000E+02	0.
0.	0.	0.	2.0000E+02

R

1.0000E+00

RICCATI SOLUTION

3.7890E+01	1.7737E-02	-3.2434E+01	-1.4915E+02
1.7737E-02	1.6054E+01	1.9598E+01	-3.7899E+01
-3.2434E+01	1.9598E+01	2.7751E+05	4.0954E+02
-1.4915E+02	-3.7899E+01	4.0954E+02	8.9448E+05

FEEDBACK MATRIX

1.1625E+01	-1.1145E+01	-2.3573E+01	-1.9485E+01

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.22134E+01	-.85599E+02
-.22134E+01	.85599E+02
-.50501E+01	-.23597E+03
-.50501E+01	.23597E+03

```
        STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

                       DX/DT = A*X + B*U

                   2J = INTEGRAL OF X'*Q*X + U'*R*U

    WHERE

                            A

 0.            0.            1.0000E+00  0.
 0.            0.            0.          1.0000E+00
-7.3321E+03    0.           -8.5630E-01  0.
 0.           -5.5709E+04    0.         -2.3603E+00


                            B

 0.
 0.
 1.0262E-01
 2.5397E-01


                            Q

 5.0000E+02  0.          0.          0.
 0.          5.0000E+02  0.          0.
 0.          0.          5.0000E+02  0.
 0.          0.          0.          5.0000E+02


                            R

 1.0000E+00


    RICCATI SOLUTION

 1.1092E+06 -3.4741E+02  2.8685E-02 -3.5088E+01
-3.4741E+02  3.2737E+06  2.6663E+02 -2.2315E-03
 2.8685E-02  2.6663E+02  1.5130E+02 -1.7958E-02
-3.5088E+01 -2.2315E-03 -1.7958E-02  5.8757E+01


    FEEDBACK MATRIX

-8.9084E+00  2.7361E+01  1.5522E+01  1.4921E+01


    CLOSED-LOOP EIGENVALUES
        REAL          IMAGINARY

     -.12246E+01    -.85619E+02
     -.12246E+01     .85619E+02
     -.30748E+01    -.23601E+03
     -.30748E+01     .23601E+03
```

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	-7.3321E+03	0.
0.	0.	0.	-5.5709E+04
1.0000E+00	0.	-8.5630E-01	0.
0.	1.0000E+00	0.	-2.3603E+00

B

3.0712E-01
-6.9453E-01
0.
0.

Q

5.0000E+02	0.	0.	0.
0.	5.0000E+02	0.	0.
0.	0.	5.0000E+02	0.
0.	0.	0.	5.0000E+02

R

1.0000E+00

RICCATI SOLUTION

6.4446E+01	8.0944E-02	-5.5234E+01	-4.3637E+02
8.0944E-02	2.7694E+01	5.7243E+01	-6.549[illegible]+01
-5.5234E+01	5.7243E+01	4.7136E+05	1.732[illegible]E+03
-4.3637E+02	-6.5498E+01	1.7321E+03	1.544[illegible]E+06

FEEDBACK MATRIX

1.9737E+01	-1.9209E+01	-5.6720E+01	-8.8528E+01

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.34594E+01	-.85558E+02
-.34594E+01	.85558E+02
-.78504E+01	-.23590E+03
-.78504E+01	.23590E+03

STEADY STATE FEEDBACK GAIN FOR THE LINEAR REGULATOR

DX/DT = A*X + B*U

2J = INTEGRAL OF X'*Q*X + U'*R*U

WHERE

A

0.	0.	1.0000E+00	0.
0.	0.	0.	1.0000E+00
-7.3321E+03	0.	-8.5630E-01	0.
0.	-5.5709E+04	0.	-2.3603E+00

B

0.
0.
1.0262E-01
2.5397E-01

Q

6.0000E+03	0.	0.	0.
0.	6.0000E+03	0.	0.
0.	0.	6.0000E+03	0.
0.	0.	0.	6.0000E+03

R

1.0000E+00

RICCATI SOLUTION

4.9752E+06	-2.3089E+04	-1.8803E+00	-7.2070E+02
-2.3089E+04	1.5129E+07	5.4899E+03	-2.7877E+00
-1.8803E+00	5.4899E+03	6.8029E+02	-1.2009E+00
-7.2070E+02	-2.7877E+00	-1.2009E+00	2.708[illegible]+02

FEEDBACK MATRIX

-1.8323E+02	5.6267E+02	6.9507E+01	6.8671E+01

CLOSED-LOOP EIGENVALUES

REAL	IMAGINARY
-.39954E+01	-.85535E+02
-.39954E+01	.85535E+02
-.98995E+01	-.23582E+03
-.98995E+01	.23582E+03

[[Ac] + [Bc][G] - [K][Cc]]

For Q=20:

					Eigenvalues:
-.7624	1.724	1.000	0		-.7517 +/- J 85.62
.6814	-1.541	0	1.000		
-7331.	-1.864	-.7411	.1047		-1.821 +/- J 236.0
-1.021	-55710	.2852	-2.101		

For Q=200:

-3.572	8.077	1.000	0		-1.800 +/- J 85.63
3.424	-7.744	0	1.000		
-7325.	-15.62	-.0275	.7829		-4.083 +/- J 235.9
5.384	-55720	2.051	-.4228		

For Q=500:

-6.062	13.71	1.000	0		-2.666 +/- J 85.65
5.899	-13.34	0	1.000		
-7316.	-36.58	.7366	1.531		-5.952 +/- J 235.8
24.93	-55760	3.942	1.429		

For Q=6000:

-22.83	51.64	1.000	0		-8.427 +/- J 86.42
22.62	-51.16	0	1.000		
-7157.	-379.7	6.277	7.047		-17.89 +/- J 232.1
484.6	-56770	17.65	15.08		

The eigenvalues of the closed loop system with residuals present are:

For Q=20:

-.8096	+/-	J	85.6224
-.3706	+/-	J	85.6263
-1.9504	+/-	J	236.0198
-1.0505	+/-	J	236.0251
-2.3139	+/-	J	462.7612
-2.3139	+/-	J	764.9125

For Q=200:

-0.0137	+/-	J	85.6291
-2.2145	+/-	J	85.6019
-0.2115	+/-	J	236.0505
-5.0518	+/-	J	236.9636
-2.3135	+/-	J	462.7740
-3.8249	+/-	J	764.9085

For Q=500:

+0.3684	+/-	J	85.6397
-3.4605	+/-	J	85.5716
+0.7140	+/-	J	235.9869
-7.8489	+/-	J	235.8623
-2.3114	+/-	J	462.8053
-3.8266	+/-	J	764.8986

For Q=6000:

+03.1510	+/-	J	85.8333
-11.9052	+/-	J	84.9542
+07.4927	+/-	J	235.1097
-26.7056	+/-	J	233.8435
-02.1238	+/-	J	463.5620
-03.9725	+/-	J	764.6554

Q=20

$$[H] = \begin{bmatrix} .7697 & .00572 & .007345 & .00004066 \\ .002269 & -.3112 & .00002155 & .004035 \\ -53.85 & -.4197 & .7699 & -.0005213 \\ -.8969 & -224.8 & -.001568 & -.3135 \end{bmatrix}$$

$$[F] = [\ .01812 \quad -.008787 \quad -.5747 \quad 2.900\ ]^T$$

$$[G] = [-.043949 \quad .1354 \quad 1.123 \quad 1.020\ ]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7697 & .00572 & .7345 & .004066 \\ .002269 & -.3112 & .002155 & .4035 \\ -.5385 & -.004197 & .7699 & -.0005213 \\ -.008969 & -2.248 & -.001568 & -.3135 \end{bmatrix}$$

$$[F]' = [\ .1812 \quad -.08787 \quad -.05747 \quad .29\ ]^T$$

$$[G] = [-.00439 \quad .01354 \quad 11.23 \quad 10.2\ ]$$

Multiply $[H]'$ and $[F]'$ by 128 and form integer matrices:

$$[H] = \begin{bmatrix} 99 & 1 & 94 & 1 \\ 0 & -\ 40 & 0 & 52 \\ -69 & -\ 1 & 99 & 0 \\ -\ 1 & -288 & 0 & -40 \end{bmatrix}$$

$$[F] = [\ 23 \quad -\ 11 \quad -7 \quad 3\ ]^T$$

$$[G] = [-\ 0 \quad 0 \quad 11 \quad 10\ ]$$

Q=200

$$[H] = \begin{bmatrix} .7513 & .02427 & .007287 & .0001933 \\ .01078 & -.3220 & .0001208 & .003964 \\ -53.38 & -2.316 & .7765 & -.001432 \\ -4.493 & -220.9 & -.005108 & -.2936 \end{bmatrix}$$

$$[F] = [\ .08209 \quad -.04310 \quad -2.688 \quad 14.14\ ]^T$$

$$[G] = [-2.3698 \quad 7.2801 \quad 8.0764 \quad 7.6288\ ]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7513 & .02427 & .7284 & .01933 \\ .01078 & -.3220 & .01208 & .3964 \\ -.5338 & -.02316 & .7765 & -.001432 \\ -.04493 & -2.209 & -.005108 & -.2936 \end{bmatrix}$$

$$[F]' = [\ .8209 \quad -.431 \quad -.2688 \quad 1.414\ ]^T$$

$$[G] = [-.23698 \quad .7280 \quad 80.764 \quad 76.288\ ]$$

Multiply [H] and [F] by 128 and form integer matrices:

$$[H] = \begin{bmatrix} 96 & 3 & 93 & 2 \\ 1 & -41 & 2 & 51 \\ -68 & -3 & 99 & 0 \\ -6 & -283 & -1 & -38 \end{bmatrix}$$

$$[F] = [105 \quad -55 \quad -34 \quad 181]^T$$

$$[G] = [\ 0 \quad 1 \quad 81 \quad 76]$$

Q=500

$$[H] = \begin{bmatrix} .7358 & .03832 & .007244 & .0003274 \\ .01788 & -.3320 & .0002152 & .003907 \\ -53.01 & -4.159 & .7834 & -.001706 \\ -7.646 & -217.9 & -.006418 & -.2759 \end{bmatrix}$$

$$[F] = [\ .1353 \quad -.07268 \quad -4.551 \quad 23.74\ ]^T$$

$$[G] = [-8.9084 \quad 27.361 \quad 15.522 \quad 14.921\ ]$$

Pseudostate Form:

$$[H]' = \begin{bmatrix} .7358 & .03832 & .7244 & .03274 \\ .01788 & -.3320 & .02152 & .3907 \\ -.5301 & -.04159 & .7834 & -.001706 \\ -.07646 & -2.179 & -.006418 & -.2759 \end{bmatrix}$$

$$[F]' = [\ 1.353 \quad -.7268 \quad -.4551 \quad 2.374\ ]^T$$

$$[G] = [-.8908 \quad 2.7361 \quad 155.22 \quad 149.21\ ]$$

Multiply [H] and [F] by 128 and form integer matrices:

$$[H]' = \begin{bmatrix} 94 & 5 & 93 & 4 \\ 2 & -42 & 3 & 50 \\ -68 & -5 & 100 & 0 \\ -10 & -279 & -1 & -35 \end{bmatrix}$$

$$[F]' = [173 \quad -93 \quad -58 \quad 304]^T$$

$$[G] = [-1 \quad 3 \quad 155 \quad 149]$$

Q=6000

$$[H] = \begin{bmatrix} .6527 & .09193 & .007073 & .001147 \\ .05591 & -.3879 & .0008353 & .003601 \\ -50.87 & -16.65 & .8357 & -.0007079 \\ -26.19 & -203.9 & .007458 & -.1694 \end{bmatrix}$$

$$[F] = [\ .4181 \quad -.2429 \quad -16.69 \quad 77.01\ ]^T$$

$$[G] = [-183.23 \quad 562.67 \quad 69.507 \quad 68.671\ ]$$

Pseudostate Form

$$[H]' = \begin{bmatrix} .6527 & .09193 & .7073 & .1147 \\ .05591 & -.3879 & .08353 & .3601 \\ -.5087 & -.1665 & .8357 & -.0007079 \\ -.2619 & -2.039 & .007458 & -.1694 \end{bmatrix}$$

$$[F]' = [\ 4.181 \quad -2.429 \quad -1.669 \quad 7.701\ ]^T$$

$$[G] = [-18.323 \quad 56.267 \quad 695.07 \quad 686.71\ ]$$

Multiply $[H]'$ and $[F]'$ by 128 and form integer matrices

$$[H] = \begin{bmatrix} 84 & 12 & 91 & 15 \\ 7 & -50 & 11 & 46 \\ -65 & -21 & 107 & 0 \\ -34 & -261 & 1 & -22 \end{bmatrix}$$

$$[F] = [535 \quad -311 \quad -214 \quad 986]^T$$

With Gain = 100 at accelerometer amplifier:

$$[F] = [\ 5 \quad -3 \quad -2 \quad 10]^T$$

Divide by 18.323 here, and Multiply by 18.323 outside:

$$[G] = [-1 \quad 3 \quad 38 \quad 37]$$

Appendix 4

Control Implementation
Discrete Form Derivation

The details of the discrete form integrations are provided below:

$$\overline{X}(t) = e^{[A]t}\,\overline{X}(0) + \int_0^t e^{[A](t-\tau)}[K]Y(\tau)\,d\tau \qquad (50)$$

Over one sample period, T,

$$\overline{X}(T) = e^{[A]T}\,\overline{X}(0) + \int_0^T e^{[A](T-\tau)}[K]Y(\tau)\,d\tau \qquad (50a)$$

Assuming $Y(\tau)$ is constant over the sample period, 0 to T,

$$\overline{X}(T) = e^{[A]T}\,\overline{X}(0) + e^{[A]T}\int_0^T e^{-[A]\tau}\,d\tau\,[K]Y(0) \qquad (50b)$$

It can be easily shown that:

$$\int_0^T e^{-[A]\tau}\,d\tau = -[A]^{-1}\,e^{-[A]}\Big|_{\tau=0}^{T} \qquad (50c)$$

Which by substitution leaves:

$$\overline{X}(T) = e^{[A]T}\,\overline{X}(0) + e^{[A]T}[A]^{-1}[[I]-e^{-[A]T}][K]Y(0) \qquad (50d)$$

Or,

$$\overline{X}(T) = e^{[A]T}\,\overline{X}(0) + [A]^{-1}[e^{[A]T} - [I]][K]Y(0) \qquad (51)$$

Appendix 5

Control Algorithm Computer Listing

The computer programs used for control implementation are listed below:

1. TASK9. This Fortran 80 main body program incorporates the storage of controller matrices' elements and commands the subroutines to:

   a) Start the system clock counters(STCLK).

   b) Perform the control function(CNTRL2M).

   c) Write the data stored(time response of the estimate of the mode) to a disk file(WRTBUF).

   d) Plot the discretized time response(PLOT).

Support subroutines are:

   a) Analog to Digital and Digital to Analog service routines(AD and DA, contained in ADIO).

   b) A simple time delay routine which allows the plotter time to respond to directed inputs(WAIT).

PROGRAM TASK9

```
      PROGRAM TASK9
      IMPLICIT INTEGER(A-Z)
C  DEFAULT IS INTEGER * 2
      DIMENSION F(4),G(4),HX(4),X(4),Y(1000)
      DIMENSION IH(4,4)
      WRITE(1,22)
 22   FORMAT(4X,'RUN NUMBER(1,2,3,4)?',/)
      READ(1,24)RUN
 24   FORMAT(I1)
C  THE FOLLOWING VALUES COME FROM EQ 66 AND 68 IN THESIS
      F(1)=105
      F(2)=-55
      F(3)=-34
      F(4)=181
      IH(1,1)=96
      IH(1,2)=3
      IH(1,3)=93
      IH(1,4)=2
      IH(2,1)=1
      IH(2,2)=-41
      IH(2,3)=2
      IH(2,4)=51
      IH(3,1)=-68
      IH(3,2)=-3
      IH(3,3)=99
      IH(3,4)=0
      IH(4,1)=-6
      IH(4,2)=-283
      IH(4,3)=-1
      IH(4,4)=-38
      G(1)=0
      G(2)=1
      G(3)=81
      G(4)=76
      DO 90 N=1,1000
 90   Y(N)=0
      DO 100 I=1,4
      X(I)=0
      HX(I)=0
 100  CONTINUE
      CALL STCLK
      CALL CNTL2M(F(1),G(1),IH(1,1),HX(1),X(1),Y(1))
      CALL WRTBUF(Y(1),1000,RUN)
      CALL PLOT(Y(1))
      STOP
      END
```

SUBROUTINE CNTL2M

```
ENTRY CNTL2M
EXTERNAL $AT,$M9
CSEG
CNTL2M:
;THIS PROOGRAM IS DERIVED FROM THE FORTRAN  COMPILER'S
;VERSION OF AN EQUIVALENT SUBROUTINE, USING TECHNIQUES
;AS  OUTLINED IN THE THESIS PAGE 8.   SOME SUBROUTINES
;ARE MADE PROGRAM SPECIFIC TO REDUCE COMPUTATION TIME.
;COMMENTS ARE DENOTED BY A C IN THE SECOND COLUMN. THE
;EQUIVALENT S/R IN FORTRAN IS NOTED BY AN F IN THE
;SECOND COLUMN:
;F        SUBROUTINE CNTL2M(F,G,IH,HX,X,Y)
;F        IMPLICIT INTEGER(A-Z)
;F        DIMENSION Y(1000),HX(4),X(4),F(4),G(4)
;F        DIMENSION IH(4,4)
;C INITIALIZE PROGRAM
.RADIX            16
                  SHLD    F
                  XCHG
                  SHLD    G
                  MVI     A,04
                  LXI     H,IH
                  CALL    $AT
;F        DO 300 K=0,253
;C REMOVE THE NEXT SEMI-COLON FOR LONGER RUN TIME
;DOK:             SHLD    K
;F        DO 300 N=1,999,2
                  LXI     H,0001
DON:              SHLD    N
;F        CALL GETTIM(Y(N+1))
                  LHLD    N
                  DAD     H
                  XCHG
                  LHLD    Y
                  DAD     D
                  SHLD    T00
                  LHLD    T00
.Z80
                  IN      A,(07AH)
                  LD      (HL),A
                  IN      A,(07BH)
                  INC     HL
                  LD      (HL),A
.8080
;F        OUT=0
                  LXI     H,0000
                  SHLD    OUT
;F        CALL AD(VIN,0,80)
                  LXI     B,FIFTY
                  LXI     D,ZERO
                  LXI     H,VIN
.Z80
```

```
                LD      (VALUE),HL
                LD      (CHAN),DE
                LD      (BASE),BC
                EX      DE,HL
                LD      A,(HL)
                LD      HL,(BASE)
                LD      C,(HL)
                OUT     (C),A
                INC     C
                LD      A,0
                OUT     (C),A
                DEC     C
NRDY:           IN      A,(C)
                AND     080H
                JR      NZ,NRDY
                INC     C
                INC     C
                IN      A,(C)
                LD      E,A
                INC     C
                IN      A,(C)
                AND     0FH
                LD      D,A
                LD      HL,(VALUE)
                LD      (HL),E
                INC     HL
                LD      (HL),D
.8080
;F       IN=VIN-2048
                LHLD    VIN
                LXI     D,0F800
                DAD     D
                SHLD    IN
;F       DO 250 I=0,3
                LXI     H,0000
DOI:            SHLD    I
;F       DO 230 J=0,3
                LXI     H,0000
DOJ:            SHLD    J
;F       230 HX(I+1)=IH(I+1,J+1)*X(J+1)+HX(I+1)
                LHLD    I
                DAD     H
                SHLD    T00
                XCHG
                LHLD    HX
                DAD     D
                SHLD    T01
                LHLD    J
                DAD     H
                DAD     H
                DAD     H
                XCHG
                LHLD    T00
                DAD     D
                XCHG
```

```
          LHLD     IH
          DAD      D
          SHLD     T02
          LHLD     J
          DAD      H
          XCHG
          LHLD     X
          DAD      D
          MOV      A,M
          INX      H
          MOV      H,M
          MOV      L,A
          XCHG
          LHLD     T02
          MOV      A,M
          INX      H
          MOV      H,M
          MOV      L,A
          CALL     $M9
          XCHG
          LHLD     T01
          MOV      A,M
          INX      H
          MOV      H,M
          MOV      L,A
          DAD      D
          XCHG
          LHLD     T01
          MOV      M,E
          INX      H
          MOV      M,D
;C        LOOP J
          LHLD     J
          INX      H
;C LOAD -(THE NUMBER OF TIMES TO LOOP IN HEX) = -4
          LXI      B,-4
          MOV      D,H
          MOV      E,L
          DAD      B
          XCHG
          JNC      DOJ
;F        X(I+1)=(HX(I+1)+F(I+1)*IN)/128
          LHLD     I
          DAD      H
          SHLD     T00
          XCHG
          LHLD     X
          DAD      D
          SHLD     T01
          LHLD     T00
          XCHG
          LHLD     HX
          DAD      D
          SHLD     T02
          LHLD     T00
```

```
                XCHG
                LHLD    F
                DAD     D
                MOV     A,M
                INX     H
                MOV     H,M
                MOV     L,A
                XCHG
                LHLD    IN
                CALL    $M9
                XCHG
                LHLD    T02
                MOV     A,M
                INX     H
                MOV     H,M
                MOV     L,A
                DAD     D
;C       DIVIDE BY 128
.Z80
                RL      L
                RL      H
                LD      L,H
                LD      A,0
                SBC     A,0
                LD      H,A
;C       SAVE VALUE OF X(I)
.8080
                LDA     I
;C       FOR MODE1: X(1),CMP 0; FOR MODE 2: X(2),CMP 1
                CMP     0
                JZ      DWN
.Z80
                LD      (XSAVE),HL
.8080
DWN:            XCHG
                LHLD    T01
                MOV     M,E
                INX     H
                MOV     M,D
;F       250  OUT=OUT-G(I+1)*X(I+1)
                LHLD    I
                DAD     H
                SHLD    T00
                XCHG
                LHLD    G
                DAD     D
                SHLD    T01
                LHLD    T00
                XCHG
                LHLD    X
                DAD     D
                MOV     A,M
                INX     H
                MOV     H,M
                MOV     L,A
```

```
                XCHG
                LHLD    T01
                MOV     A,M
                INX     H
                MOV     H,M
                MOV     L,A
                CALL    $M9
                XCHG
                LHLD    OUT
                MOV     A,E
                SUB     L
                MOV     L,A
                MOV     A,D
                SBB     H
                MOV     H,A
                XRA     A
                SUB     L
                MOV     L,A
                SBB     H
                SUB     L
                MOV     H,A
                SHLD    OUT
;C      LOOP I
                LHLD    I
                INX     H
;C LOAD: -(THE NUMBER OF TIMES TO LOOP IN HEX) = -4
                LXI     B,-4
                MOV     D,H
                MOV     E,L
                DAD     B
                XCHG
                JNC     DOI
;F      OUT=OUT/128
                LHLD    OUT
;C      DIVIDE BY 128
.Z80
                RL      L
                RL      H
                LD      L,H
                LD      A,0
                SBC     A,0
                LD      H,A
.8080
;F      VOUT=OUT+2048
                SHLD    OUT
                LXI     D,0800
                DAD     D
                SHLD    VOUT
;F      CALL DA(VOUT,0,72)
                LXI     B,FORTY8
                LXI     D,ZERO
                LXI     H,VOUT
.Z80
                LD      A,(DE)
                ADD     A,A
```

```
                INC     A
                PUSH    HL
                PUSH    BC
                POP     HL
                LD      C,(HL)
                ADD     A,C
                LD      C,A
                POP     HL
                LD      A,(HL)
                OUT     (C),A
                DEC     C
                INC     HL
                LD      A,(HL)
                OUT     (C),A
.8080
;F        300 Y(N)=IN
                LHLD    N
                DAD     H
                DCX     H
                DCX     H
                XCHG
                LHLD    Y
                DAD     D
                SHLD    T00
;C              LHLD    IN    (USE IF WANT  Y(N)=IN)
;C Y(N) = XSAVE = X(1) OR X(2) DEPENDING ON ABOVE INFO
                LHLD    XSAVE
                XCHG
                LHLD    T00
                MOV     M,E
                INX     H
                MOV     M,D
;C        LOOP N
                LHLD    N
                INX     H
                INX     H
;C LOAD -(THE NUMBER OF TIMES TO LOOP(1000) IN HEX)
                LXI     B,-03E8
                MOV     D,H
                MOV     E,L
                DAD     B
                XCHG
                JNC     DON
;C LOOP K  REMOVE SEMI-COLONS FOR LONGER RUN TIME
;               LHLD    K
;               INX     H
;C LOAD -(THE NUMBER OF TIMES TO LOOP(254) IN HEX)
;               LXI     B,-0FE
;               MOV     D,H
;               MOV     E,L
;               DAD     B
;               XCHG
;               JNC     DOK
;F        RETURN
                RET
```

```
DSEG
        F:        DW      0
        G:        DW      0
        IH:       DW      0
        HX:       DW      0
        X:        DW      0
        Y:        DW      0
        I:        DW      0
        J:        DW      0
        K:        DW      0
        N:        DW      0
        OUT:      DW      0
        T00:      DW      0
        VIN:      DW      0
        IN:       DW      0
        T01:      DW      0
        T02:      DW      0
        VOUT:     DW      0
        FIFTY:    DW      50
        FORTY8:   DW      48
        ZERO:     DW      0
        VALUE:    DW      0
        CHAN:     DW      0
        BASE:     DW      0
        XSAVE:    DW      0
        END
```

SUBROUTINE ADIO

```
.Z80
            ENTRY   AD
;           A/D SERVICE ROUTINE - CAPT BRIGGS(AFIT/ENY, WPAFB,OH)
;           FORTRAN CALLABLE: CALL AD(VALUE,CHAN,BASE)
;           GET ONE SAMPLE FROM THE CHAN'TH CHANNEL
;           ON THE  A/D BOARD WITH BASE ADDRESS 'BASE'
AD:         LD      (VALUE),HL
            LD      (CHAN),DE
            LD      (BASE),BC
            EX      DE,HL     ;HL->CHAN
            LD      A,(HL)    ;GET CHAN NO.
            LD      HL,(BASE)
            LD      C,(HL)    ;GET BASE I/O ADDRESS TO C REG FOR OUTING
            OUT     (C),A     ;MODE 0 TO CHAN NO.
                              ;USES BASE ADDRESS IN C REG
            INC     C         ;POINT TO START CONVERSION PORT
            LD      A,0
            OUT     (C),A     ;START CONVERSION
            DEC     C         ;POINT TO BASE REGISTER
NRDY:       IN      A,(C)     ;GET STATUS
            AND     080H      ;BIT 7 IS STATUS, =1 IS BUSY
            JR      NZ,NRDY   ;NOT ALL 0'S => BUSY
            INC     C         ;POINT TO BASE ADD+1
            INC     C         ;POINT TO DRL
            IN      A,(C)     ;LOW BYTE OF VALUE
            LD      E,A
            INC     C         ;POINT TO DRH
            IN      A,(C)     ;HIGH BYTE OF VALUE
            AND     0FH       ;MASK OUT HIGH NIBBLE
            LD      D,A       ;DE=VALUE
            LD      HL,(VALUE)          ;HL->WHERE TO PUT VALUE
            LD      (HL),E    ;PUT LOW BYTE OF VALUE
            INC     HL
            LD      (HL),D    ;THAT GIVES THE CALLER THE VALUE
            RET
VALUE:      DW      0         ;STORAGE FOR ADDRESS OF VALUE
CHAN:       DW      0         ;STORAGE FOR ADDRESS OF CHANNEL NO
BASE:       DW      0         ;STORAGE FOR ADDRESS OF BASE ADDRESS
;
.Z80
ENTRY DA
;           CALL DA(VAL,CHAN,BASE)
;           CHAN IS 0
;           BASE IS 72(BASE 10)
DA:         LD      A,(DE)              ;GET CHAN
            ADD     A,A                 ;DOUBLE IT
            INC     A                   ;ADD ONE
            PUSH    HL                  ;SAVE VAL
            PUSH    BC                  ;
            POP     HL                  ;HL=>BASE
            LD      C,(HL)              ;C=LOW BYTE OF BASE
            ADD     A,C                 ;
```

```
        LD      C,A                 ;C=LOW BYTE VALUE OF PORT
        POP     HL                  ;GET VAL
        LD      A,(HL)              ;GET LOW BYTE
        OUT     (C),A               ;PUT LOW BYTE
        DEC     C                   ;C=HIGH BYTE PORT
        INC     HL                  ;HL=>HI BYTE
        LD      A,(HL)              ;GET HI BYTE
        OUT     (C),A               ;PUT HI BYTE
        RET
        END
```

SUBROUTINE PLOT

```
      SUBROUTINE PLOT(Y)
      IMPLICIT INTEGER(A-Z)
      DIMENSION Y(1000)
      EXTERNAL DA,WAIT
C  PLOT THE VALUES IN ARRAY(Y(N))
      YMX=0
      DO 200 N=1,399,2
      Y(N+1)=(Y(N+1))/2
      IF(Y(N).GT.0) GO TO 110
      YCOMP=-Y(N)
      GO TO 115
110   YCOMP=Y(N)
115   CONTINUE
      IF (YCOMP.LT.YMX) GO TO 120
      YMX=YCOMP
120   YMAX=2048+YMX+YMX/10
      YMIN=2048-YMX-YMX/10
      Y(N)=2048+Y(N)
      Y(N+1)=2048-Y(N+1)
      M=3
C  PEN UP
      CALL DA(3500,3,72)
C  WAIT FOR PEN TO COME UP
      CALL WAIT(M)
C  GO TO Y-VALUE
      CALL DA(Y(N),2,72)
C  GO TO X-VALUE
      CALL DA(Y(N+1),1,72)
C  WAIT FOR PEN TO STOP MOVING
      CALL WAIT(M)
C  PEN DOWN
      CALL DA(2048,3,72)
      CALL WAIT(M)
200   CONTINUE
C  WHEN DONE PLOTTING,DRAW BOUNDARIES
C  GO TO THE ORIGIN
      CALL DA(3500,3,72)
      CALL WAIT(M)
      CALL DA(2048,1,72)
      CALL DA(2048,2,72)
      CALL DA(2048,3,72)
      CALL WAIT(M)
C  GO AROUND TWICE
      DO 220 I=1,2
      CALL DA(YMAX,2,72)
      CALL WAIT(M)
      CALL DA(Y(N+1),1,72)
      CALL WAIT(M)
      CALL DA(YMIN,2,72)
      CALL WAIT(M)
      CALL DA(2048,1,72)
220    CALL WAIT(M)
```

```
      CALL DA(2048,2,72)
      XM=2048
      V=(YMAX-2048)/30
      PV=2048+V
      MV=2048-V
      U=(YMAX-2048)/5
      DO 240 I=1,7
C  INCREMENT X-AXIS
      CALL WAIT(M)
      CALL DA(2048,3,72)
      XM=XM+200
      CALL WAIT(M)
      CALL DA(XM,1,72)
      CALL WAIT(M)
      CALL DA(PV,2,72)
      CALL WAIT(M)
      CALL DA(MV,2,72)
      CALL WAIT(M)
240   CALL DA(2048,2,72)
C  RETURN TO ORIGIN
      CALL WAIT(M)
      CALL DA(Y(N+1),1,72)
      CALL WAIT(M)
      CALL DA(2048,1,72)
      CALL WAIT(M)
      CALL DA(2048,2,72)
      YM=2048-6*U
C  INCREMENT THE Y-AXIS
      DO 270 I=1,10
      YM=YM+U
      CALL WAIT(M)
      CALL DA(YM,2,72)
      CALL WAIT(M)
      CALL DA(2055,1,72)
      CALL WAIT(M)
270   CALL DA(2048,1,72)
      CALL WAIT(M)
      CALL DA(YMAX,2,72)
      CALL WAIT(M)
      CALL DA(2048,2,72)
      CALL WAIT(M)
      CALL DA(3500,3,72)
      RETURN
      END
```

SUBROUTINE WRTBUF

```
        SUBROUTINE WRTBUF(BUF,NS2,RUN)
        IMPLICIT INTEGER(A-Z)
        DIMENSION BUF(1)
        DIMENSION ZBUF(8)
        ST=0
        WRITE(1,50)
50      FORMAT(3X,'MODE 1',5X,'TIME',3(5X,'MODE 1',4X,'TIME'))
        N=NS2/8
        R=RUN+5
        DO 800 JA=1,N
        DO 90  C=1,8
        P=ST+C
90      ZBUF(C)=BUF(P)
        WRITE(1,100)(ZBUF(K),K=1,8)
        WRITE(R,100)(ZBUF(K),K=1,8)
100     FORMAT(/,4(2X,I7,3X,I6))
        ST=ST+8
800     CONTINUE
        NT=NS2-N*8
        IF(NT.EQ.0) GO TO 910
        DO 890 D=1,NT
        P=ST+D
890     ZBUF(D)=BUF(P)
        WRITE(1,900)(ZBUF(M),M=1,NT)
        WRITE(R,900)(ZBUF(M),M=1,NT)
900     FORMAT(/,4(2X,I7,3X,I6))
910     CONTINUE
        RETURN
        END
```

SUBROUTINE STCLK

```
ENTRY STCLK
.Z80
STCLK:
        LD A,017H  ;CHANNEL 1 CTRL WD =TIME/16
        OUT (079H),A
        LD A,09AH  ;TIME CONSTANT
        OUT (079H),A
        LD A,057H  ;CHANNEL 2 CNTRL WD=CTR
        OUT (07AH),A
        LD A,0FFH  ;TIME CONSTANT=256(BASE 10)
        OUT (07AH),A
        LD A,057H  ;CHANNEL 3 CNTRL WD=CTR
        OUT (07BH),A
        LD A,0FFH  ;TIME CONSTANT
        OUT (07BH),A
        RET
        END
```

Appendix 6

Experiment Checklist

1. Turn on all equipment - leave High Voltage Dc (HVDC) off.
2. Check accelerometer firmly in place.
3. Check all connections (especially micro dot) secure.
4. Assure HVDC dials are fully CCW and turn on.
5. Select operate on analog computer/check potentiometers.
6. Simultaneously set both HVDC dials at 200 ma.
7. Turn plotter on, center/check.
8. Set beam initial displacement or white noise generator.
9. Place disk #3(operating system) in drive A (label faces right).
10. Place disk #5 (program) in drive B (label faces right).
11. "Boot up" the system by pressing reset button.
12. Type: B: (return).
13. Type: TASK91 (return) for mode 1 output, and TASK92 for mode 2 output. TASK91 is just TASK9 linked with CNTL2M which outputs the estimate of mode 1. TASK92 is formed similarly using CNTL2M which outputs the estimate of mode 2. Both give discrete time response. For the continuous case use TASK91N or TASK92N which are formed by deleting the appropriate ; in CNTL2M.
14. Enter run number, push return, and release the initial displacement mechanism, or push RUN for noise input.
15. Data will appear on screen and in a disk file, Fort0(run number plus five).Dat, as four pairs of value and time (1 clock cycle = .00005013 sec.).

Appendix 7

Library

This file contains a list of the information stored in room 147 pertaining to Dr. Calico's Flexible Beam Experiment.

Vol. I.

A. Microsoft Fortran-80 Documentation - Microsoft.

1. Fortran-80 Reference Manual - statements, functions, syntax.
2. Fortran-80 User's Manual - compiler commands and error messages.
3. Microsoft Utility Software Manual - Macro-80 assembler, LINK-80 Linker Loader,LIB-80 Lib Manager.

B. MC 5.16 Vibrations Laboratory Experiments - Winter 1982.

1. Oscilloscope, RMS meter, Oscillator.
2. Shaker, Power Supply, Power Amplifier, Freq Counter.
3. Accelerometers, Accelerometer Amplifiers.
4. Unknown Accelerometer Calibration.
5. Cantilever Beam Response.
6. Measure Resistance, Output Impedance.
7. Oscillograph, Galvanometer Operation.
8. Vibration Decay Experiment.

C. CP/M Seminar Lecture Notes.

Vol II EE 6.87 Microcomputer Lab - Alan Ross

A. Course Notes and Assignments.

B. ZCPR Documentation.

C. SID Symbolic Intruction Debugger User's Guide.

D. ZSID Command Summary.

E. MACRO-80 Assembler Reference Manual.

F. WM Screen-Oriented Text Editor User's Manual

E. Manual 0: S-100 Bus.

F. Manual 1: Z80 CPU Technical Manual.

G. Manual 2: Z80 CPU Technical Manual and Applications Note (8251 Specification Sheets contained within).

H. Manual 3: Z80 PIO Technical Manual.

I. Manual 4: Z80 CTC Product Specification.

J. Manual 5: Z80 Family Interrupt Structure Tutorial.

K. Manual 6: SBC-100 Single Board Computer.

Vol III. Mainframe Hardware.

A. Model 910 Terminal - Televideo.

B. S-100 Bus Mainframe - Electronic Control Technology.

1. Expandoram II - Random Access Memory SD Systems.
2. SD Monitor -Intructional Publication.
3. SBC-100 Single Board Computer.
4. Mostek 3882 CTC Technical Manual - Mostek.
5. S-100 Bus Extender Board/Logic Probe Kit.
6. S-100 D/A Converter Board - Techmar Inc.
7. S-100 A/D Converter Board - Techmar Inc.
8. AIM- 12 Analog Input Module - Dual Systems

Control.

9. AOM- 12 S-100 D/A Converter - Dual Systems Control.

10. HP3721A Correlator Documentation.

11. HP3720A Spectrum Display Documentation.

Vol IV. Background Information.

A. PACOSS - Statement of Work - Passive and Active Control of Space Structures.

B. DTIC (Defense Technical Information Center) Literature Search.

C. ASIAC (Aerospace Structures Information and Analysis Center) Literature Search.

D. User's Guide to DTIC.

E. Control of a Flexible Satellite Via Elimination of Observation Spillover - Janiszewski/Calico - AFIT.

F. Hardware Demonstration of Flexible Beam Control Schaechter JPL, California Institute of Technology.

G. An Experimental Investigation of Modern Modal Control-Herrick, Canavin, Strunce - Draper Labs.

Vol V. Tarbell Disk Control/Digital Research CP/M Pubs.

A. Tarbell Basic - Tarbell Electronics.

B. Tarbell Basic 15.4 Improvements and Changes.

C. Tarbell CP/M 2.0 (BIOS)/User's Guide.

D. Tarbell Double Density Floppy Disk Interface-Owner's Manual.

E. Intro to CP/M Features and Facilities- Digital

Research.

F. ED: Context Editor for theCP/M DiskSystem User's Manual.

G. CP/M Dynam'c Debugging Tool (DDT)- User's Guide.

H. CP/M Assembler (ASM) - User's Guide.

I. CP/M 2 User's Guide.

J. CP/M 2 Alteration Guide.

K. CP/M 2 Interface Guide.

Vol VI Additional Software/Studor's Thesis

A. TOTAL USERS MANUAL - An interactive computer-aided design program for digital and continuous control system analysis and synthesis.

B. OPTCON - Solution of Linear Quadratic Optimal Control Problem - Witt, Mirmak, & Ray March 1982

C. Thesis

D. Disk Programs

1. Used in thesis

2. Future applications

VITA

George Frederick Studor, Jr. was born in Syracuse, New York on November 22, 1954. Soon after high school graduation in 1972 he began his Air Force service as a cadet at the USAF Academy. Graduating in 1976 with a Bachelor of Science in Astronautical Engineering, Lieutenant Studor went on to USAF Undergraduate Pilot Training which he completed successfully in August, 1977. He was assigned to the 41st TAS, Pope Air Force Base, North Carolina, and was upgraded to C-130 aircraft commander. In June 1981, Captain Studor was assigned to the School of Engineering, Air Force Institute of Technology, to enter the Masters Degree Program in Astronautical Engineering.

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Control Sequences- Computer Programming
Control Test Vehicles

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental demonstation of modern modal control of a flexible clamped-clamped beam in bending was accomplished. Pole placement techniques in conjunction with a Leuenberger observer were used for controller development. Available microcomputer computational capabilities drove the reduced order model to a two mode representation. The controllers, designed with varying degrees of robustness, demonstrated the limitations of reduced order controllers in even the simplest

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of systems. Sensor and actuator position are demonstrated to be of paramount importance in the modern controller LQ design.